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Title: Meet the Lightslingers

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Meet the Lightslingers

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Electromagnetic applications such as Radar or telecommunications use decades-old technology: dipoles, dish/horn antennas, phased arrays.

- High transmit powers
- Environmental/health concerns.
- Overload of available frequency spectrum.

Need new approach!

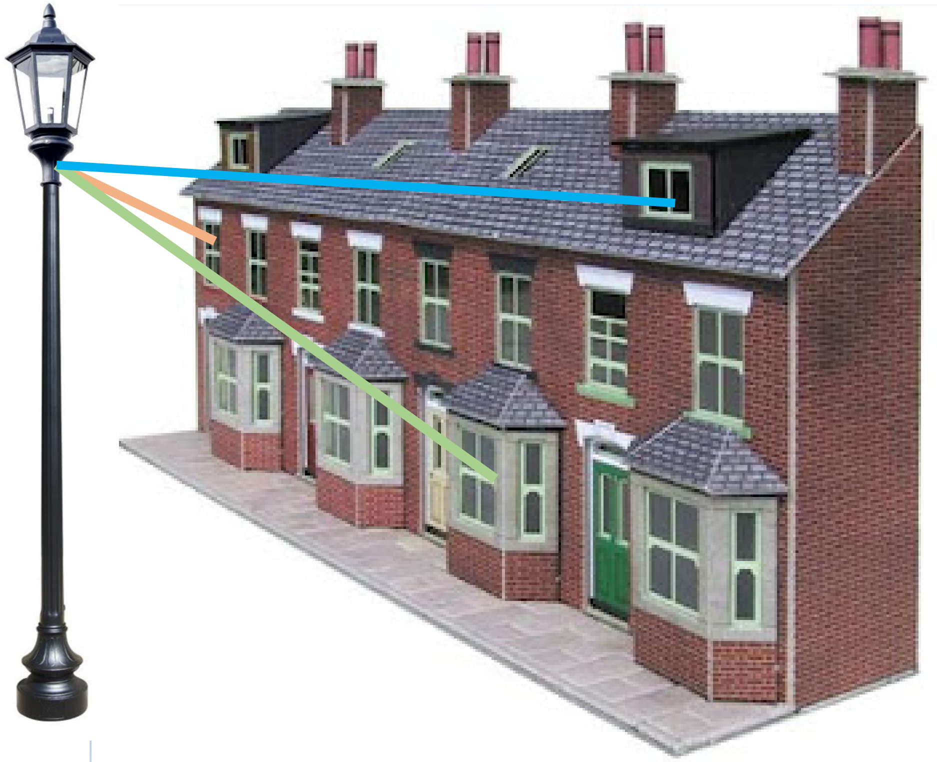
Hostile plane picks up stray signals

Friendly drone

Conflict zone: several (semi-) autonomous vehicles exchange data about threats, targets; don't want hostiles to know what they know.

The problem: conventional radio is not very directional unless antenna is enormous; selectivity is via narrow frequency bands. Situation has not changed much since Battle of Jutland (1916). Security compromised.

Coming soon: 5G local network concept: small array (~35 GHz) mounted on existing infrastructure; sends signals successively into individual apartments or rooms.



Can your neighbor see what you ordered on Amazon? Will it be possible to work on sensitive projects at home?

Lightslingers: Polarization-current antennas

Maxwell's 3rd and 4th equations:

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$$

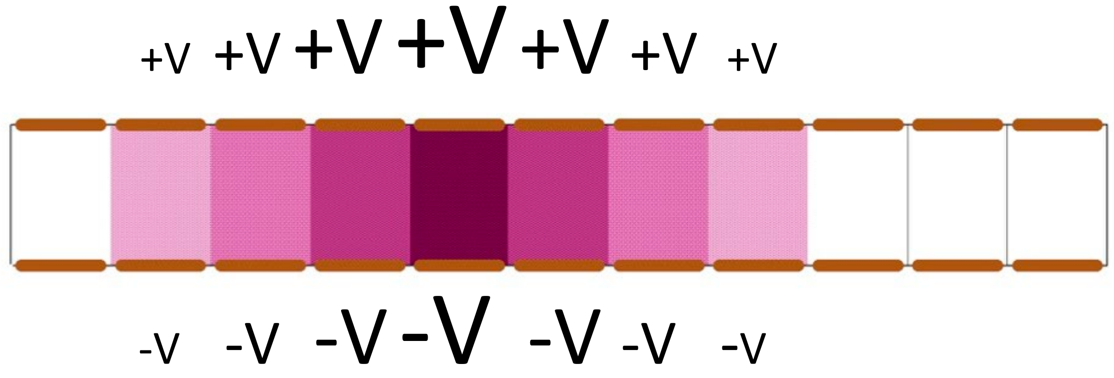
$$\nabla \times \mathbf{H} - \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} = \mathbf{J}_{\text{free}} + \frac{\partial \mathbf{P}}{\partial t}$$

- Left-hand side: propagation of electromagnetic radiation.
- Right-hand side: source terms.

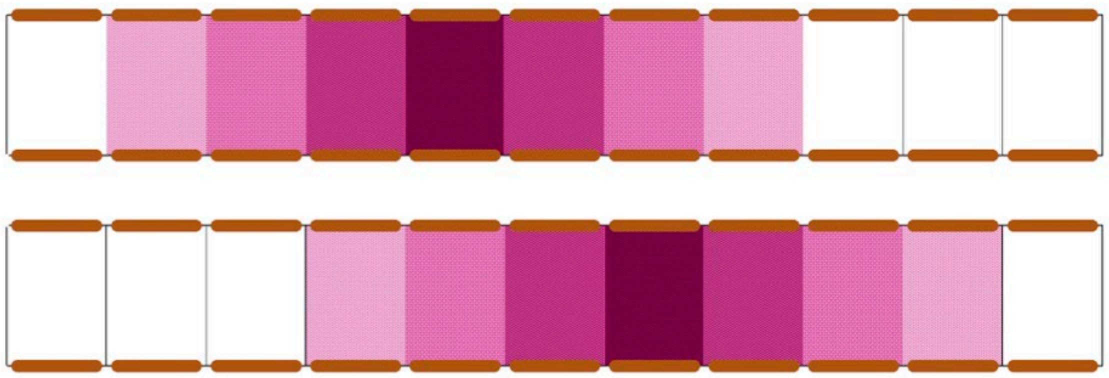
$\mathbf{J}_{\text{free}}$ = current of free electrons (ordinary antennas, light bulbs, synchrotrons).

Our antennas use a moving **polarization current** $\partial\mathbf{P}/\partial t$ as the source.

Making polarization $\mathbf{P}$: apply voltages to Cu electrodes either side of a strip of alumina:



Making it move: shift voltages to neighbouring electrodes: polarization moves as well.



It moves, so we have $\partial\mathbf{P}/\partial t$.

Lightslingers: Polarization-current antennas

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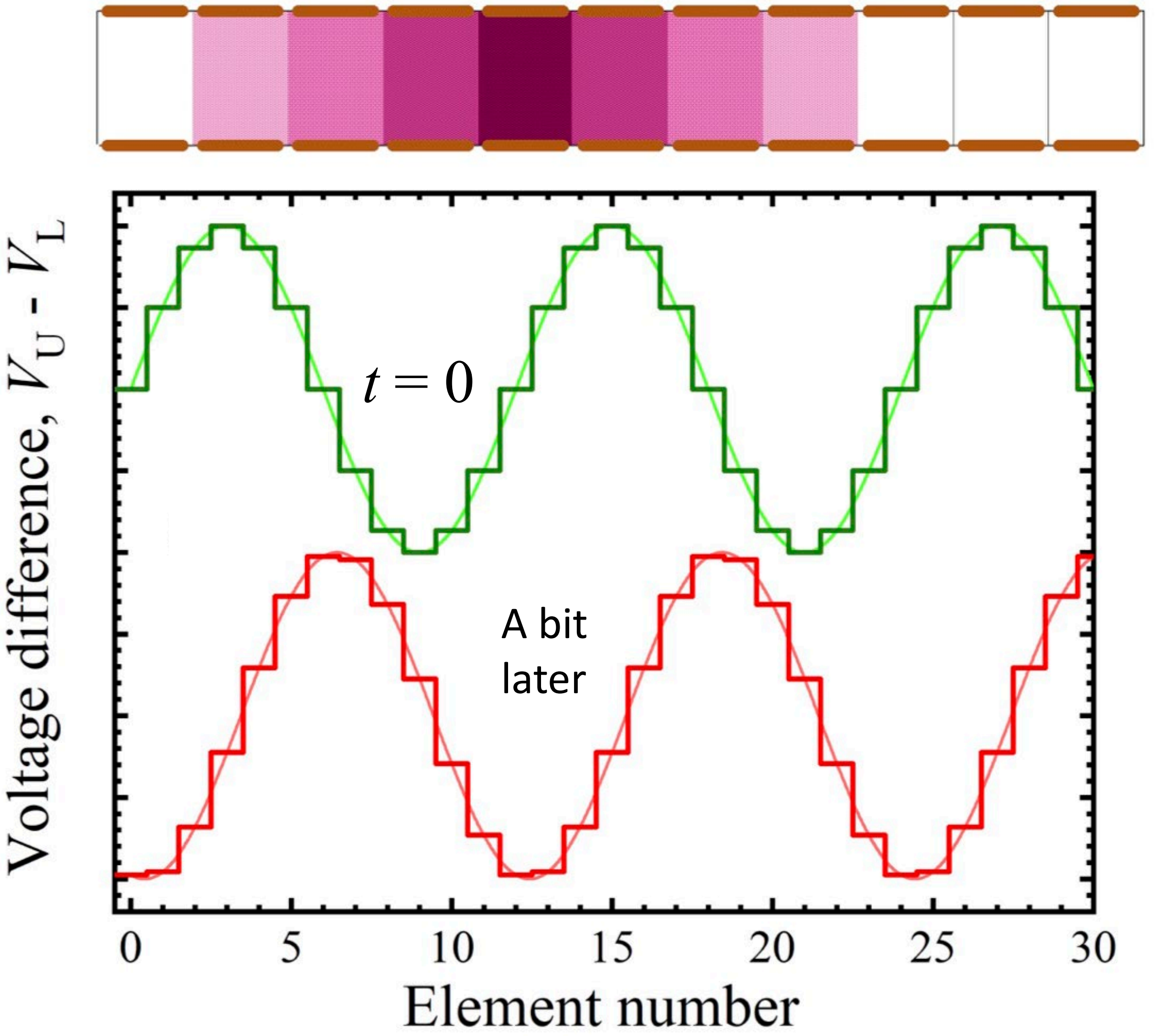
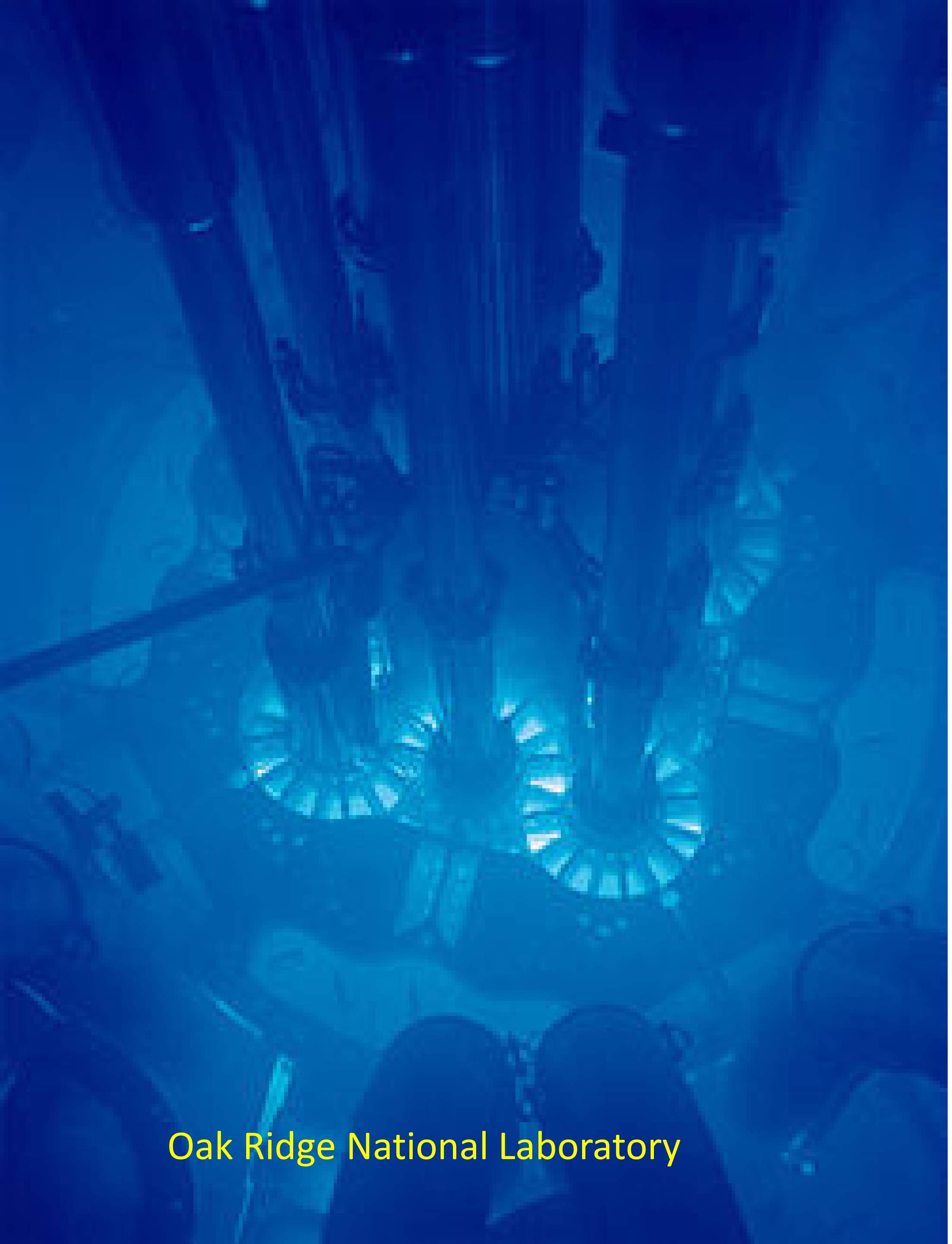
In practice, we feed signals with suitable phase differences to each electrode pair.

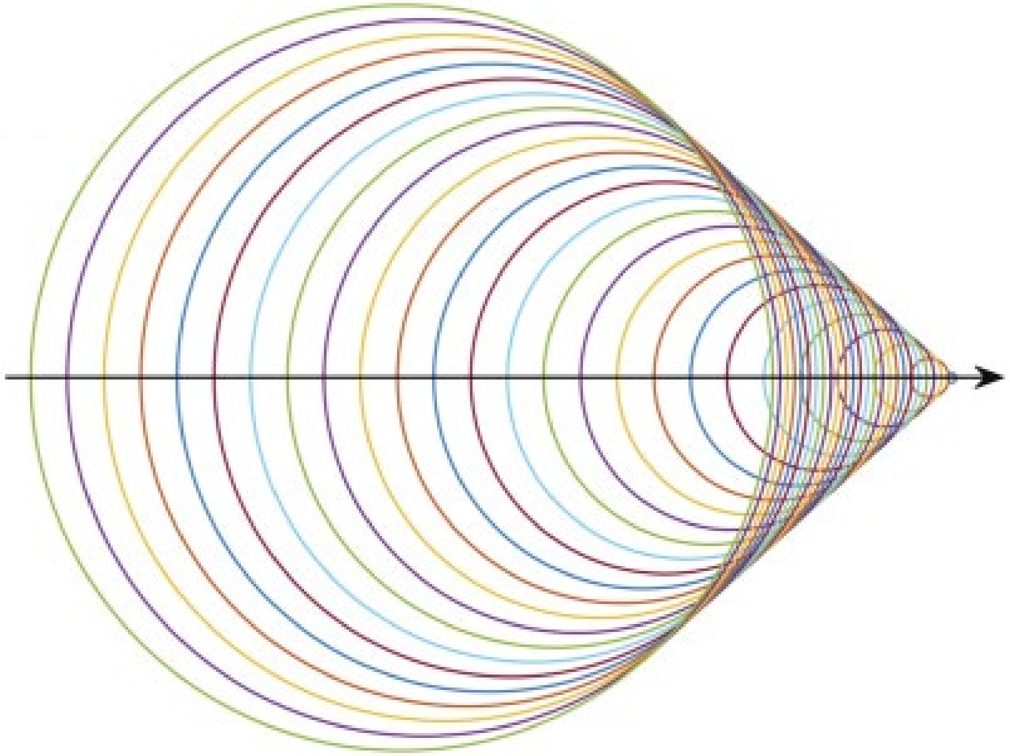


Speeds can be set by varying the phase differences between adjacent electrode pairs.

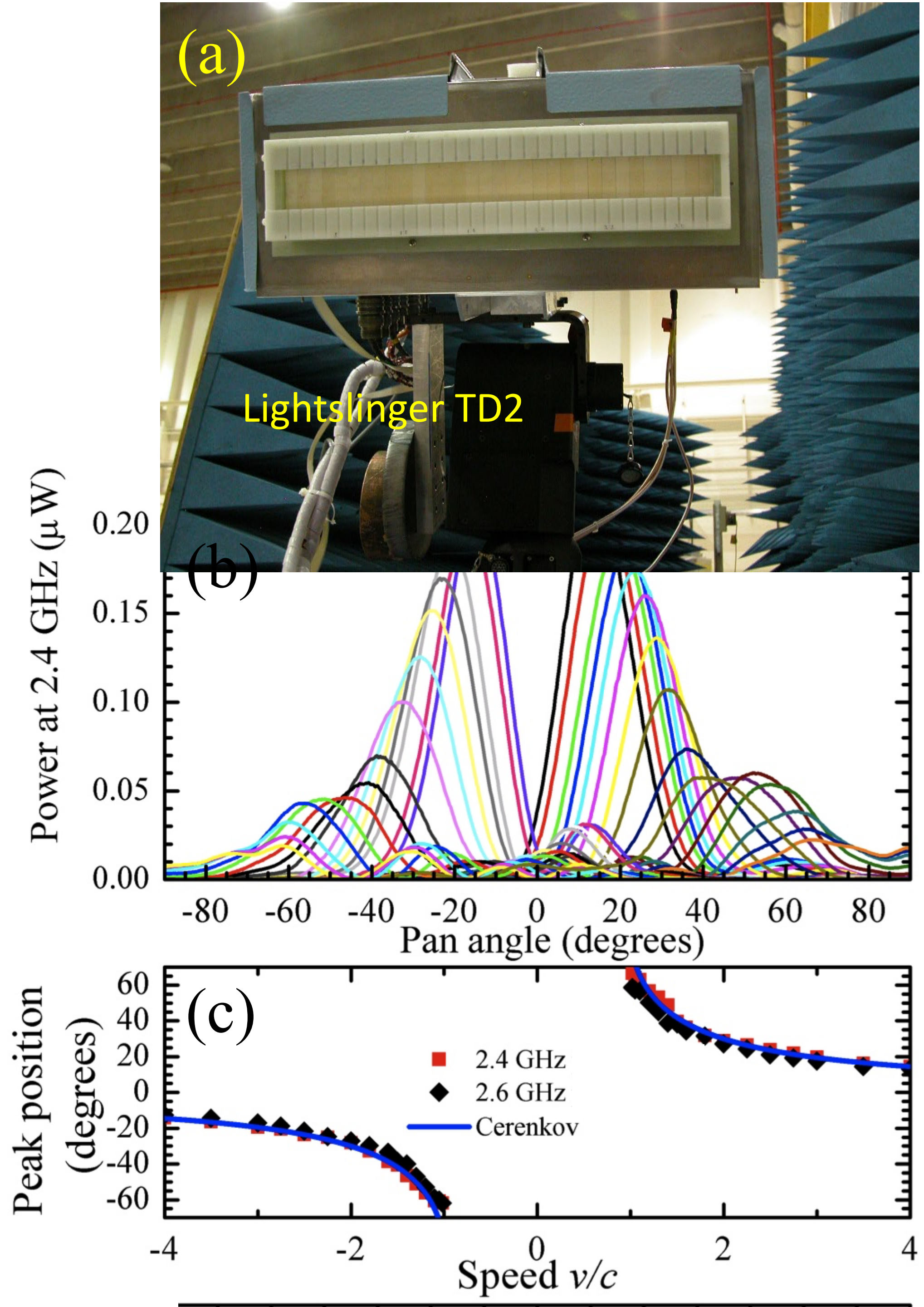


Conventional Čerenkov Radiation

Usually, this is due to charged particles that travel faster than the speed of light *c*′ in a medium such as water.

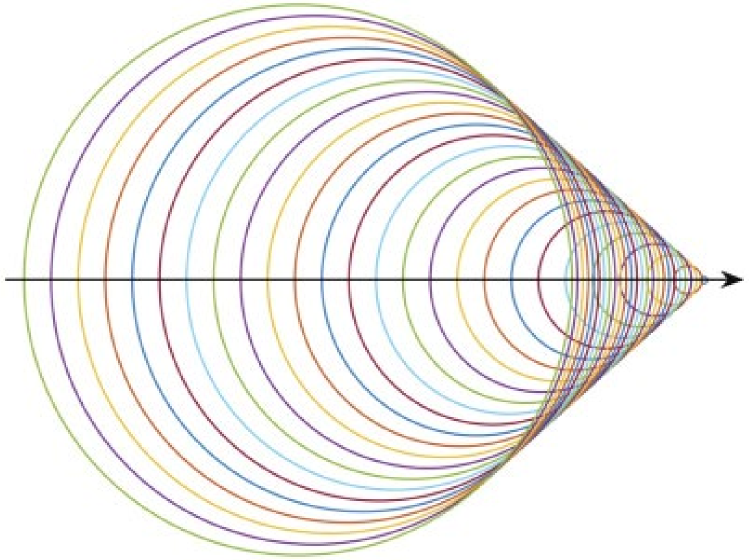


Analogous to Mach cone in acoustics: angle sin θ $=c'/v$.



Test: *Vacuum Vavilov-Čerenkov* effect

- Remember that polarization current is like a current of charged particles.
- Now, however, the "charge" travels faster than light in a vacuum.
- Run polarization current through antenna at many different speeds.
- Emitted radiation comes off at the correct angle: it is *vacuum Vavilov-Čerenkov radiation*.



Why bother? Isn't this just a phased array? NO!

Phased array

- The signal in a phased array is emitted from a series of discrete elements - point-like (electrically small antennas- ESAs) or line-like (dipoles).
- Skin depth effects in the metal elements mean that the emission is from surface currents.

Lightslinger:

- The signal is emitted from the ***entire volume of the dielectric by a volume-distributed current.***
- This eliminates fringing effects- antenna is more efficient.
- Other novel things we can do with a volume-distributed source: accelerate it smoothly, for example.
- Antenna can be any shape, optimized to a particular application.

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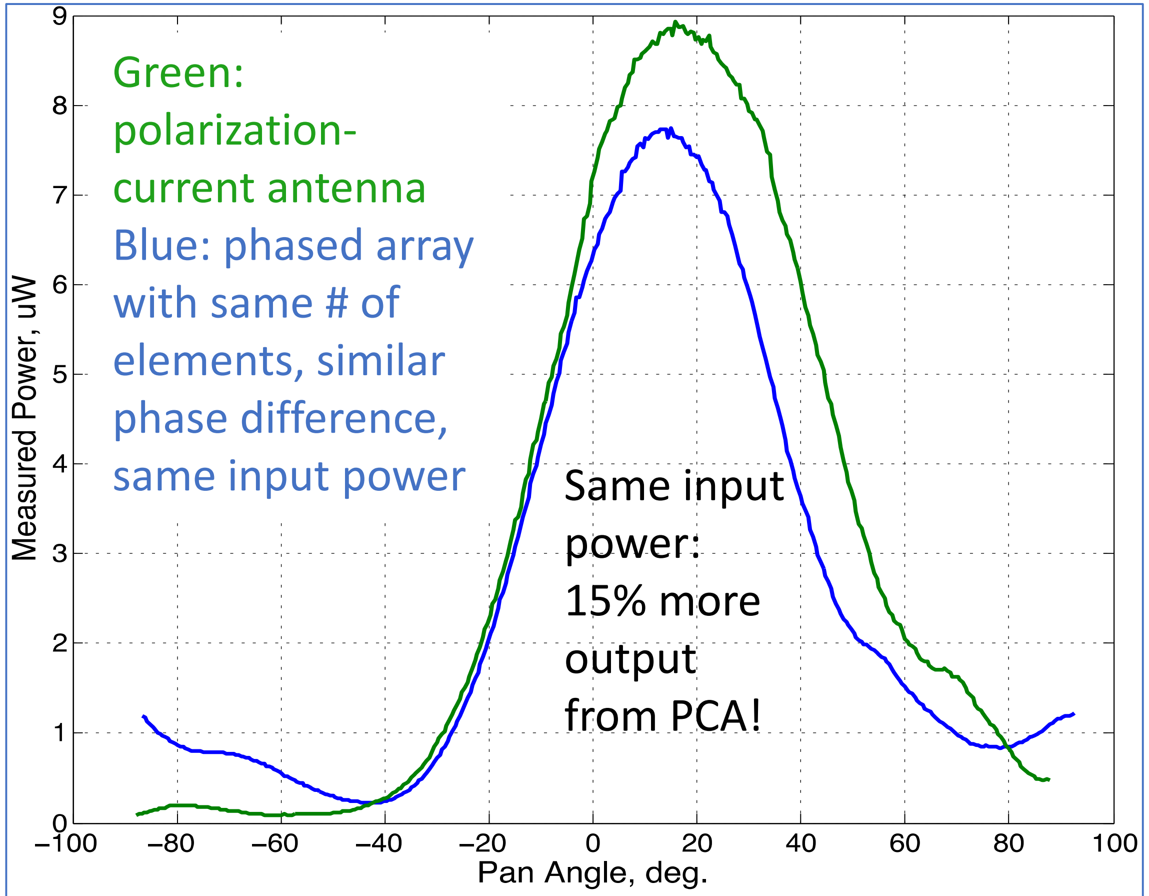
Lightslinger:

- The signal is emitted from the ***entire volume of the dielectric by a volume-distributed current.***
- **This eliminates fringing effects- antenna is more efficient. (No radiation from back.)**
- Other novel things we can do with a volume-distributed source: accelerate it smoothly, for example.
- Antenna can be any shape, optimized to a particular application.



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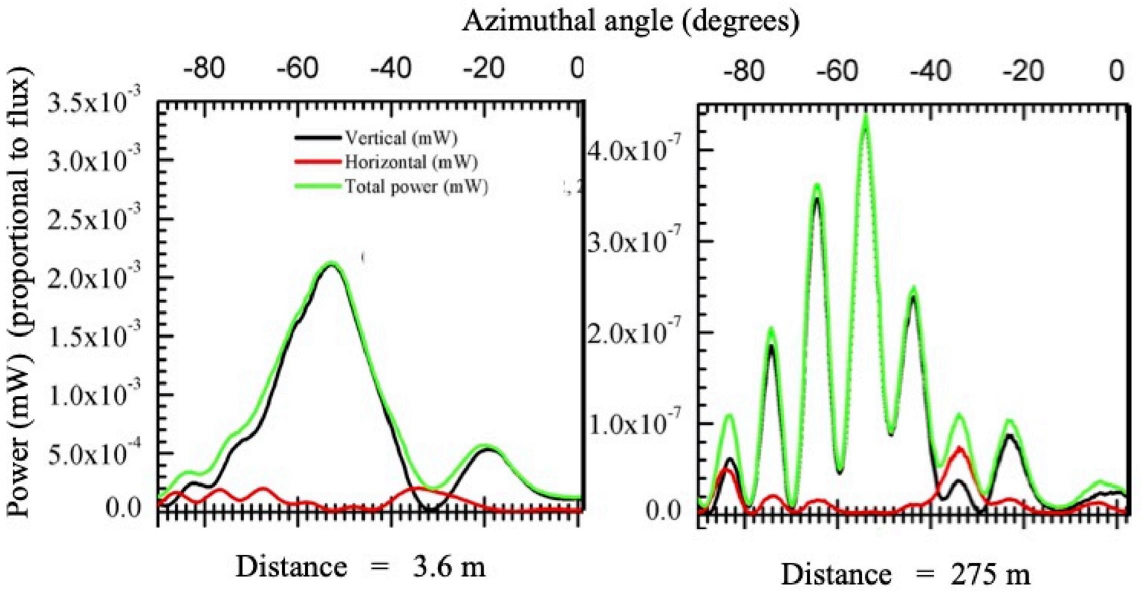

Data from tests at Sandia National Laboratory. At large distances, antenna acts like a coherent source. Peaks are a radio analogue of *laser speckle*. Ward Patitz (Range Superintendent) "I have never seen a phased array behave like this". **DIRECTED ENERGY APPs.** (More on similar things later.)

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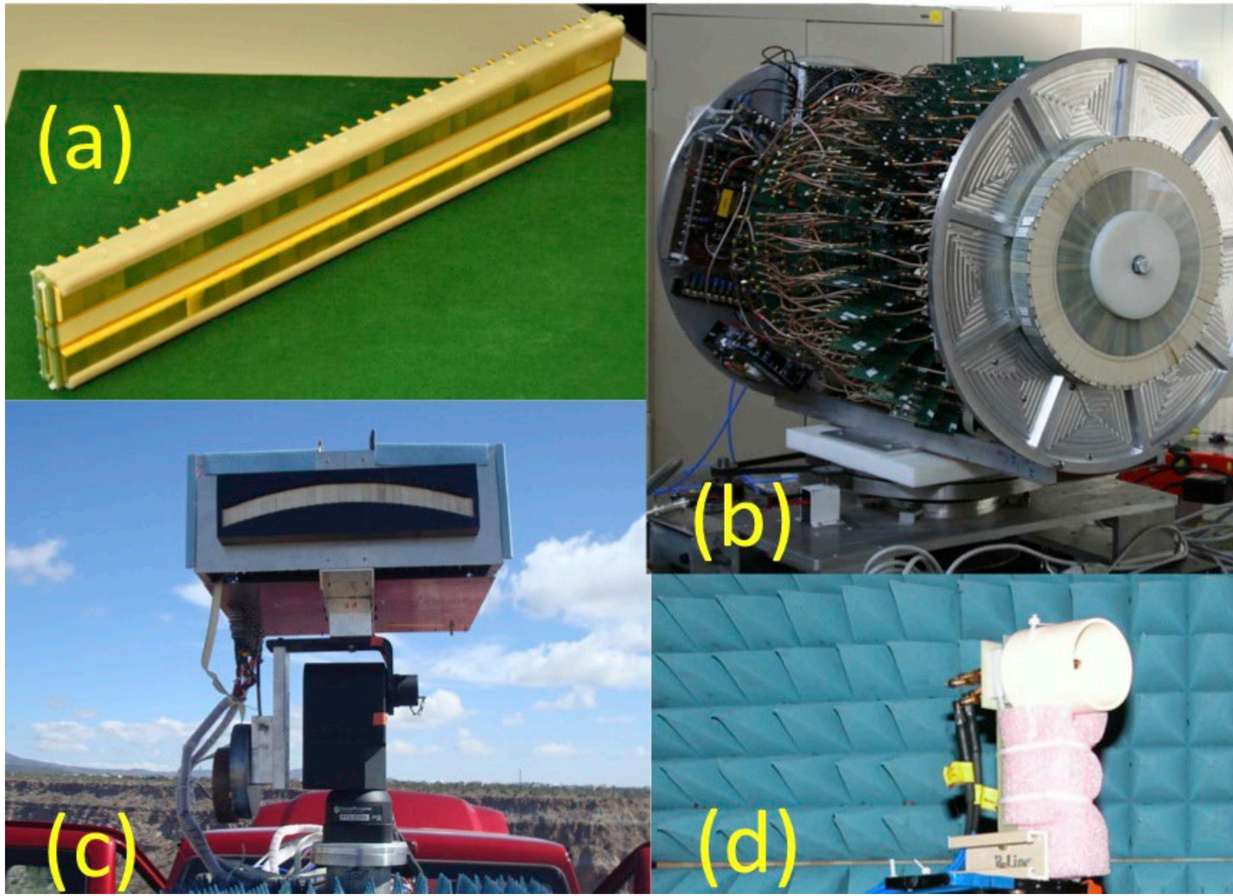


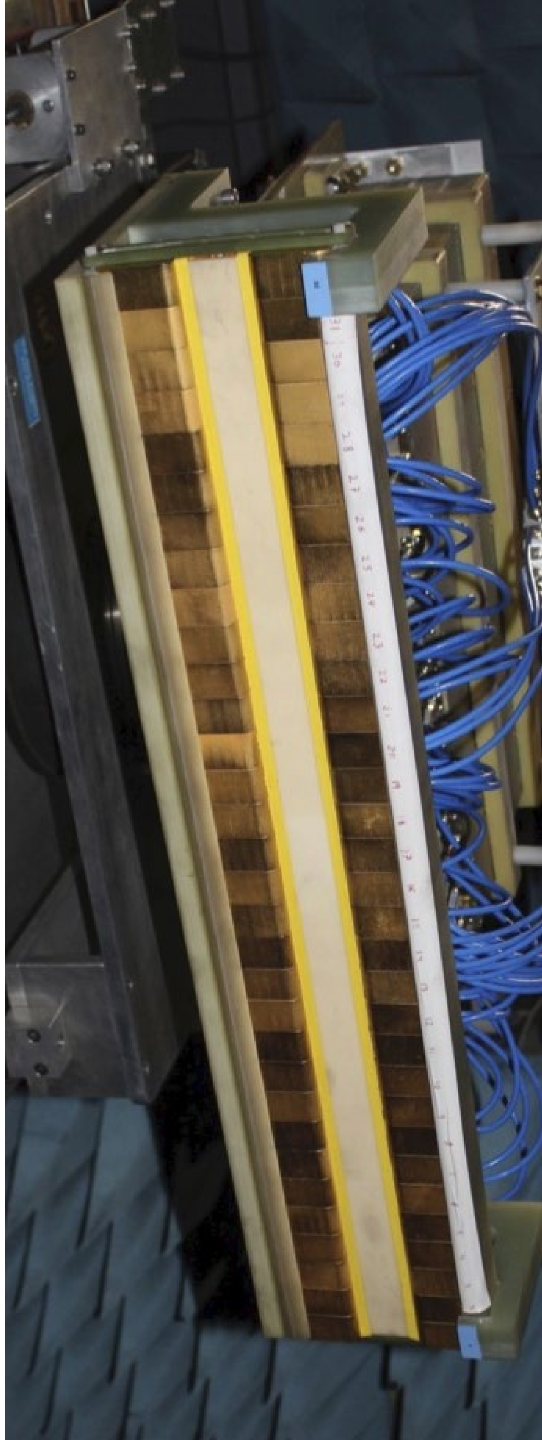
Conventional roles: why ***Lightslingers*** are better

(a) SWAP

- **Size**: *Lightslinger* is c. 25 % smaller than equivalent phased array.
- **Weight**: Lightslingers can be made very thin, with almost no metal components.
- **Assembly**: current base-station antennas have hundreds of small parts, assembled by hand in China; *Lightslingers* are monolithic structures amenable to 3D printing or CNC milling plus robot assembly. Let's bring antenna manufacture home to the US!
- **Power**: *Lightslinger* elements are designed only to emit forward- no fringing effects- c. 15 % more efficient than phased array.

(b) Design

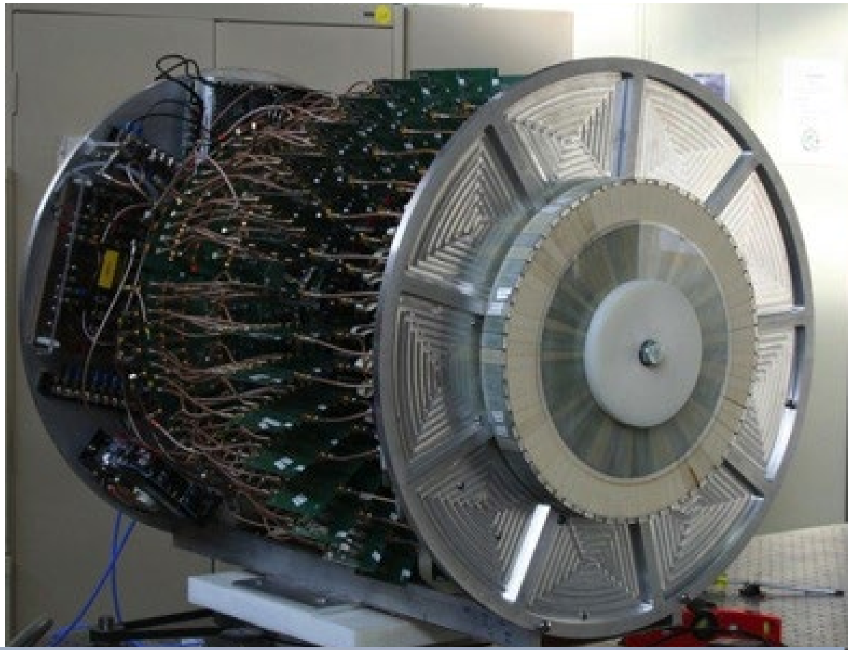
- *Lightslinger* shape can be tailored to particular role- use topology optimization/machine learning to design most efficient antenna possible.
- *Lightslinger* could take any shape- e.g., conforming to the bodywork of a vehicle or robot.
- *Lightslinger* can be made from ceramics- can be embedded seamlessly in ceramic armor of UAVs.

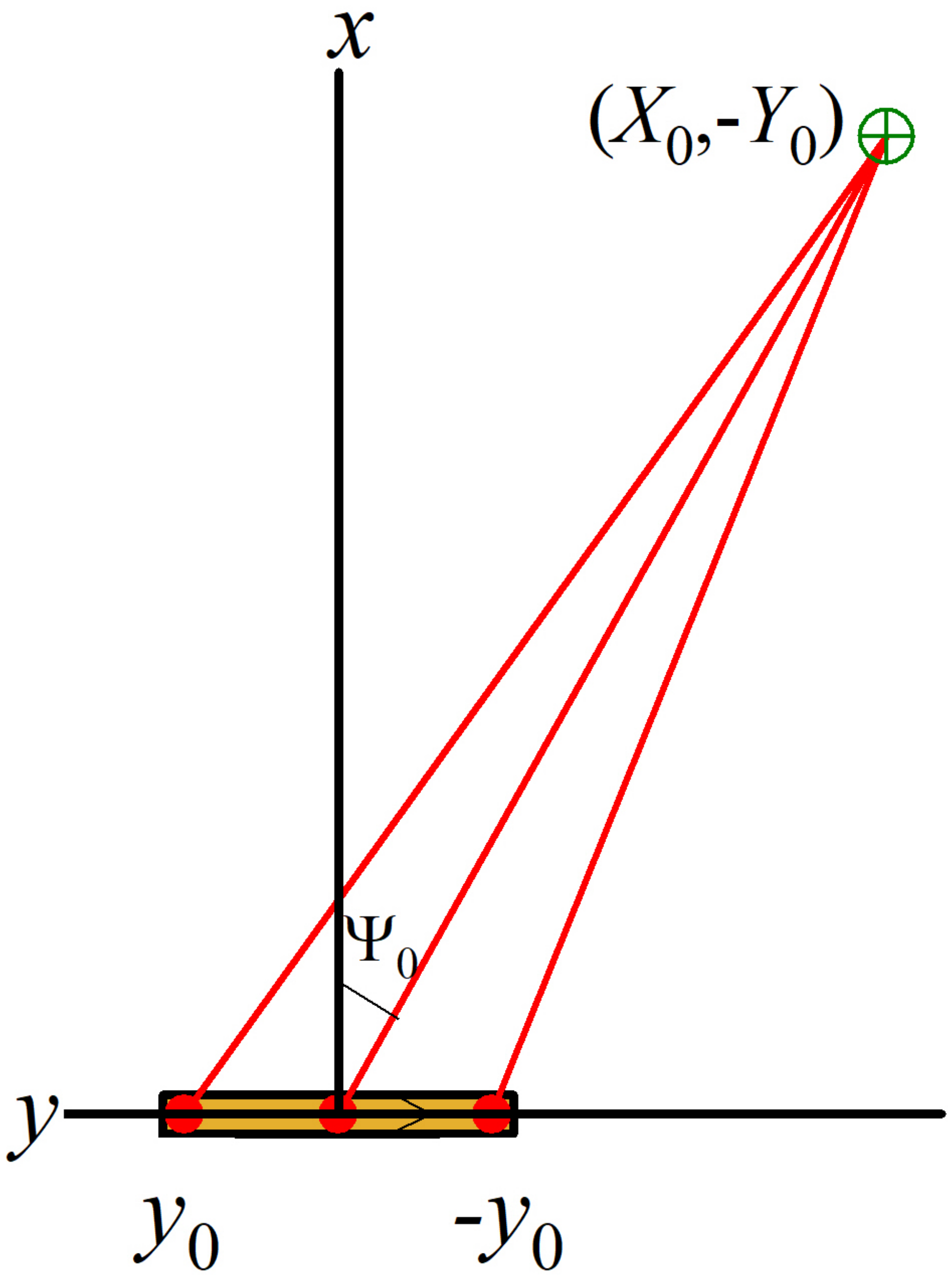


New roles unique to *Lightslingers*

1. Directed energy/coherent sources.
2. Optical angular momentum.
3. Confusing phase fronts to make RADAR less vulnerable to countermeasures (patent issued).
4. Information focus by broadband transmission from an accelerated polarization current (patent).

As an example, focus on no. 4.





Experimental concept

Run the antenna so that a small blob of polarization current travels such that the component of its velocity towards a target $\oplus$ is always *c*. Source to target distance is *r:*

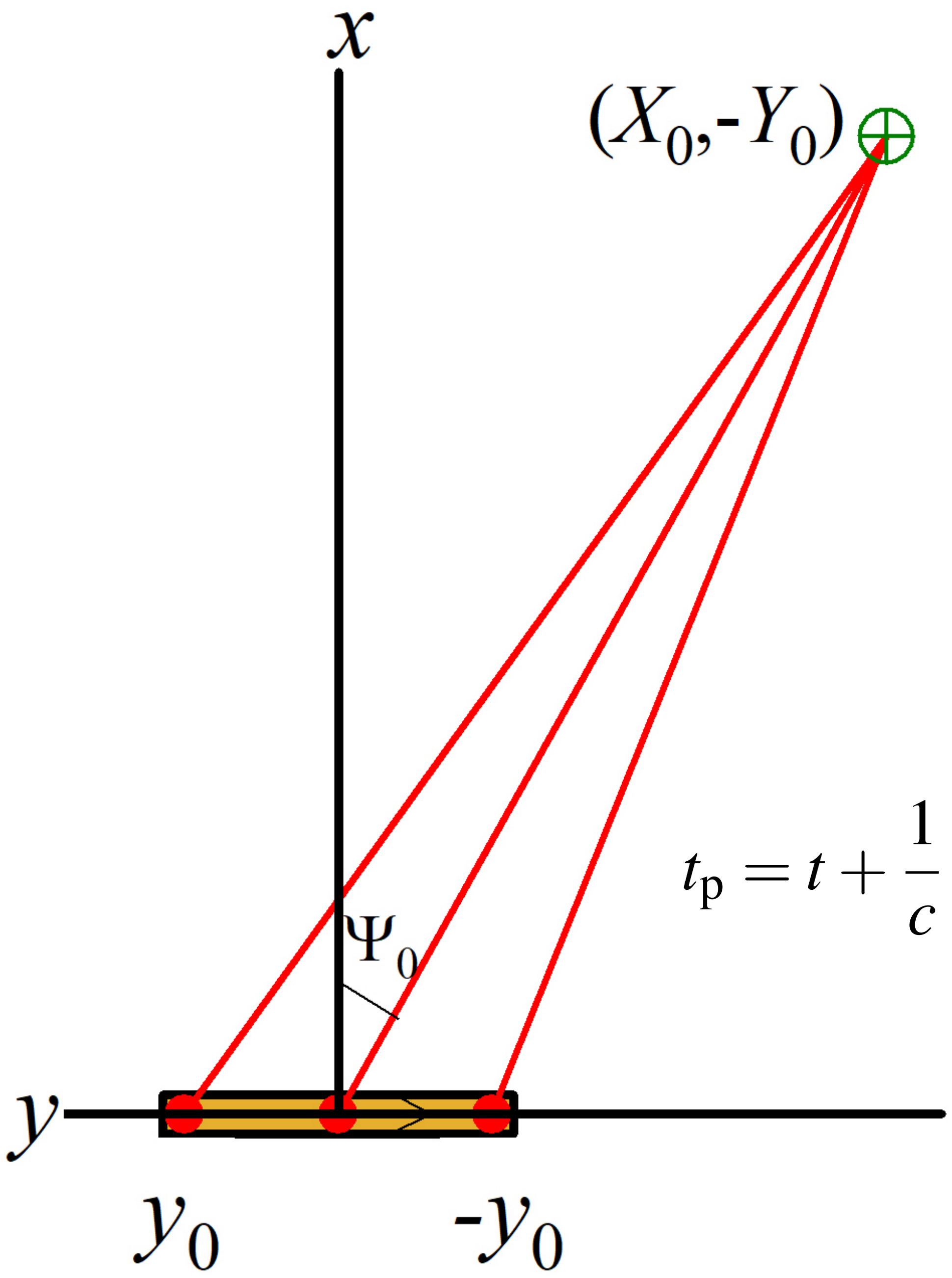
$$r^2 = X_0^2 + (Y_0 + y)^2$$

Now $\mathrm{d}r/\mathrm{d}t = -c$ so that blob speed along antenna is:

$$\frac{\mathrm{d}y}{\mathrm{d}t} = -c\frac{\left[X_0^2 + (Y_0 + y)^2\right]^{\frac{1}{2}}}{Y_0 + y}$$

Integrating, the time that the blob is at position y is

$$t = \frac{1}{c}\left[(X_0^2 + (Y_0 + y_0)^2)^{\frac{1}{2}} - (X_0^2 + (Y_0 + y)^2)^{\frac{1}{2}}\right]$$



Experimental concept

Run the antenna so that a small blob of polarization current travels such that the component of its velocity towards a target ⊕ is always *c*.

The time that the blob is at position y is

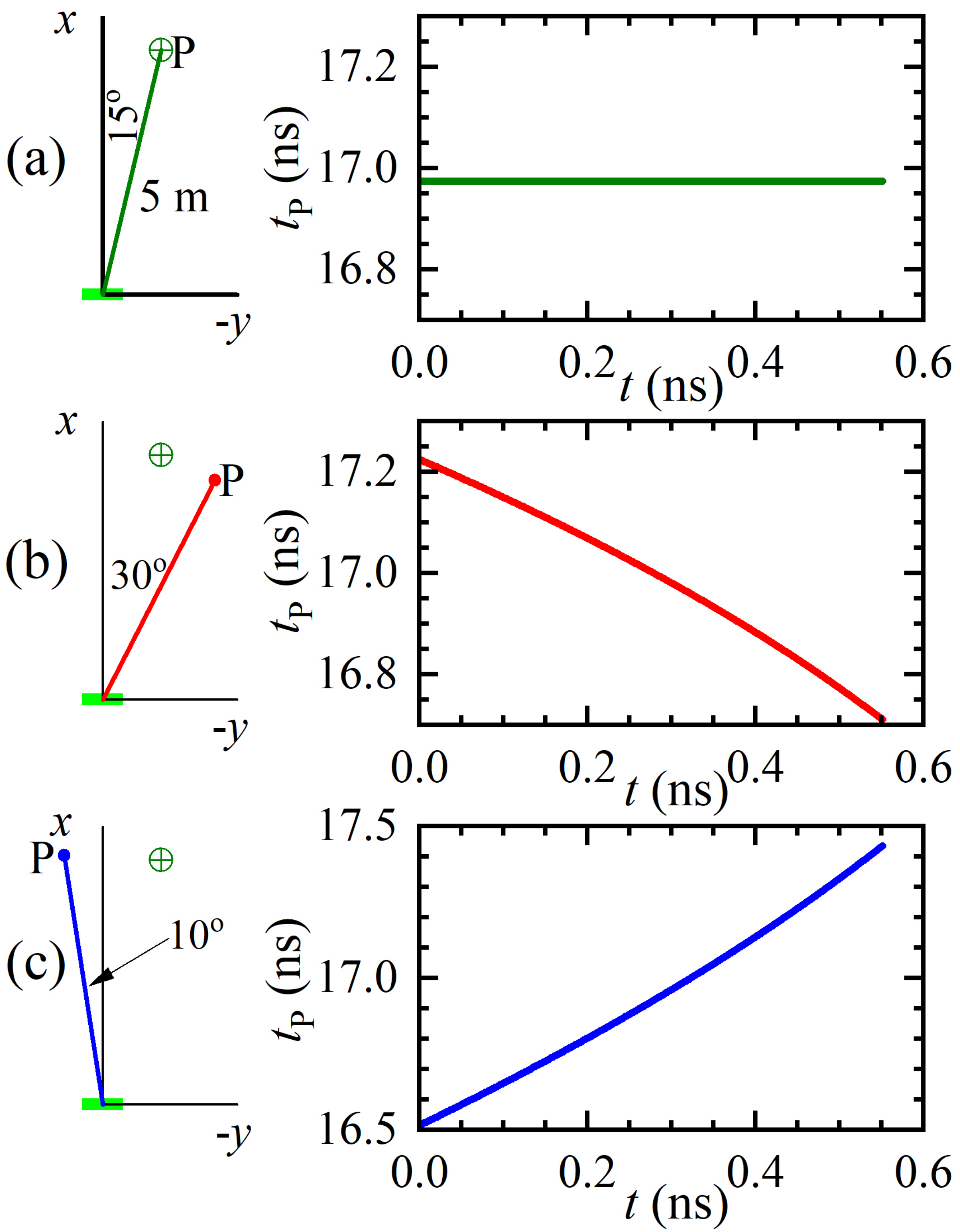
$$t = \frac{1}{c}\left[(X_0^2 + (Y_0 + y_0)^2)^{\frac{1}{2}} - (X_0^2 + (Y_0 + y)^2)^{\frac{1}{2}}\right]$$

The blob emits light as it goes along. Consider a general receiver position $(X,\text{-}Y)$. The radiation arrives here at

$$t_{\mathrm{p}} = t + \frac{1}{c}(X^2 + (Y + y)^2)^{\frac{1}{2}} = \frac{1}{c}\Big[(X_0^2 + (Y_0 + y_0)^2)^{\frac{1}{2}} - (X_0^2 + (Y_0 + y)^2)^{\frac{1}{2}} + (X^2 + (Y + y)^2)^{\frac{1}{2}}\Big]$$

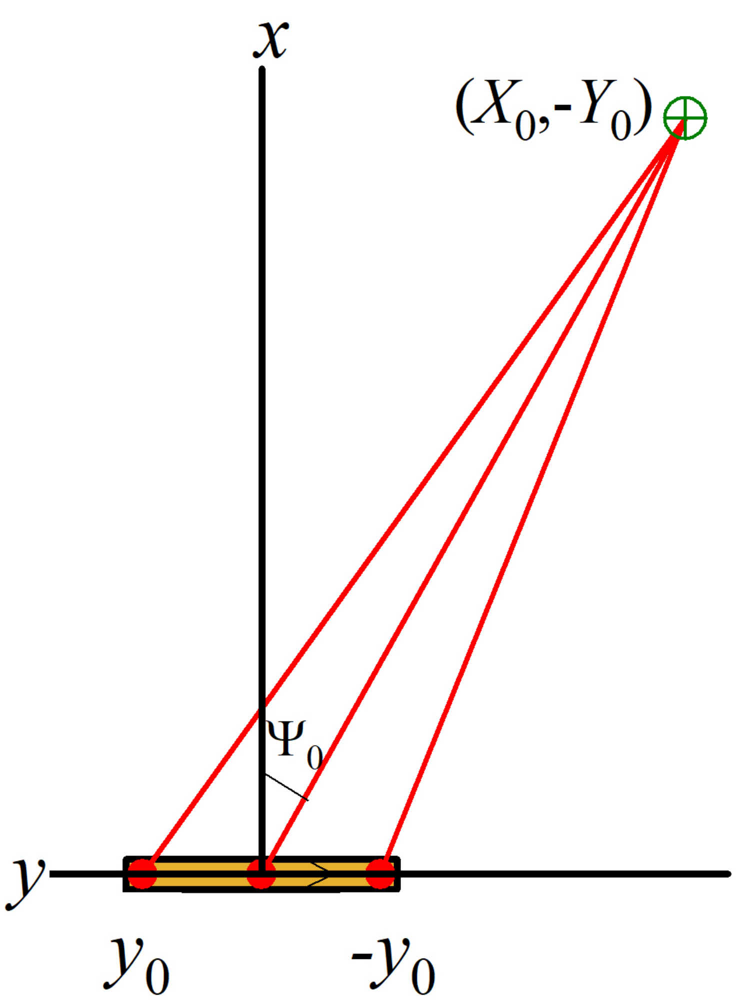
Nota bene: if, and only if, $(X,\text{-}Y) = (X_0,\text{-}Y_0)$ this expression yields a constant.

Set the target position 5 m away from the centre of the antenna, 15º "off boresight".
Plot arrival time of radiation from blob at target versus emission time. It's a constant (see previous equation).



Now put receiver P at 30º off boresight. The arrival time of the radiation is a function of the emission time.

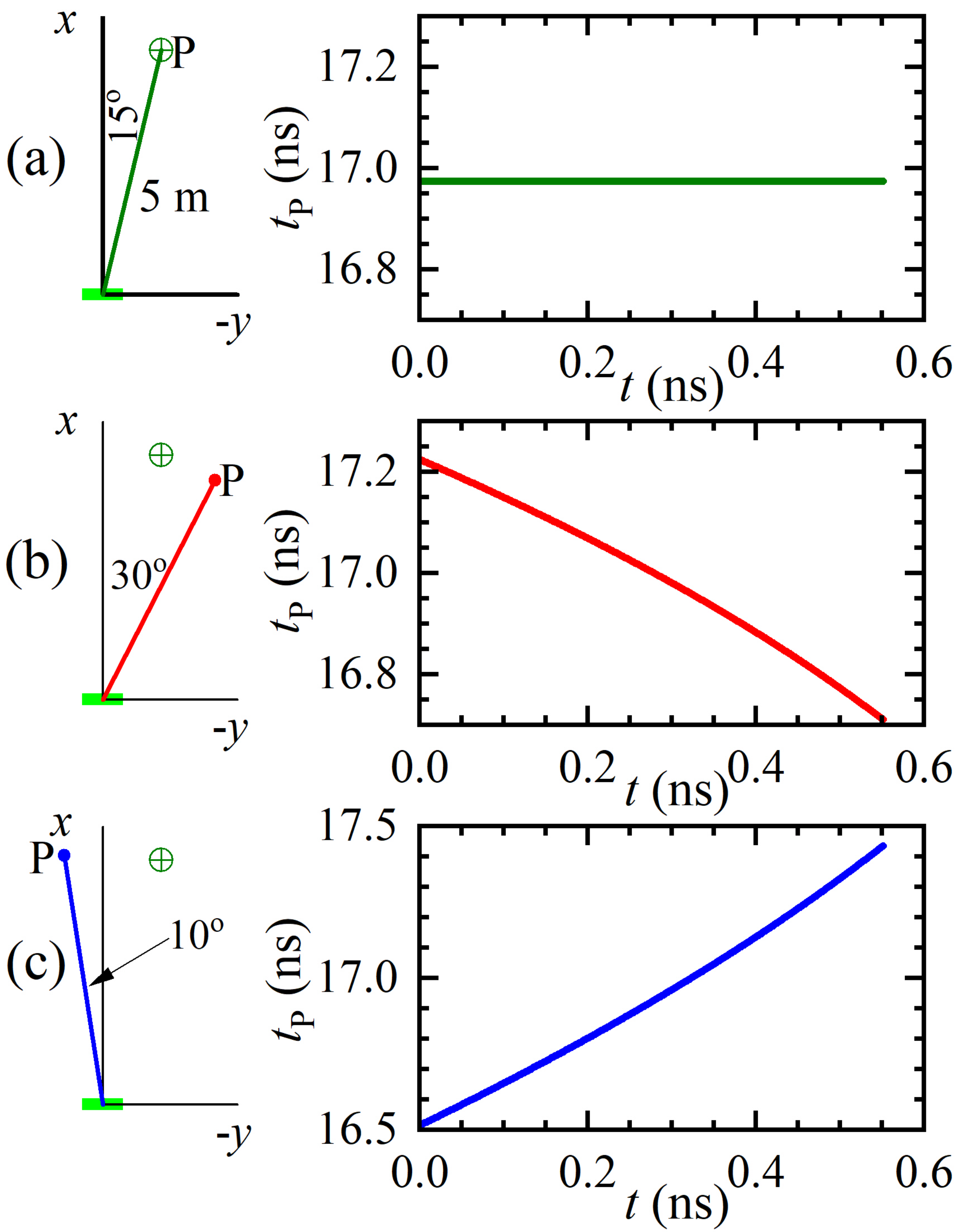
Place receiver P at -10º off boresight. The arrival time of the radiation is a *different* function of the emission time.



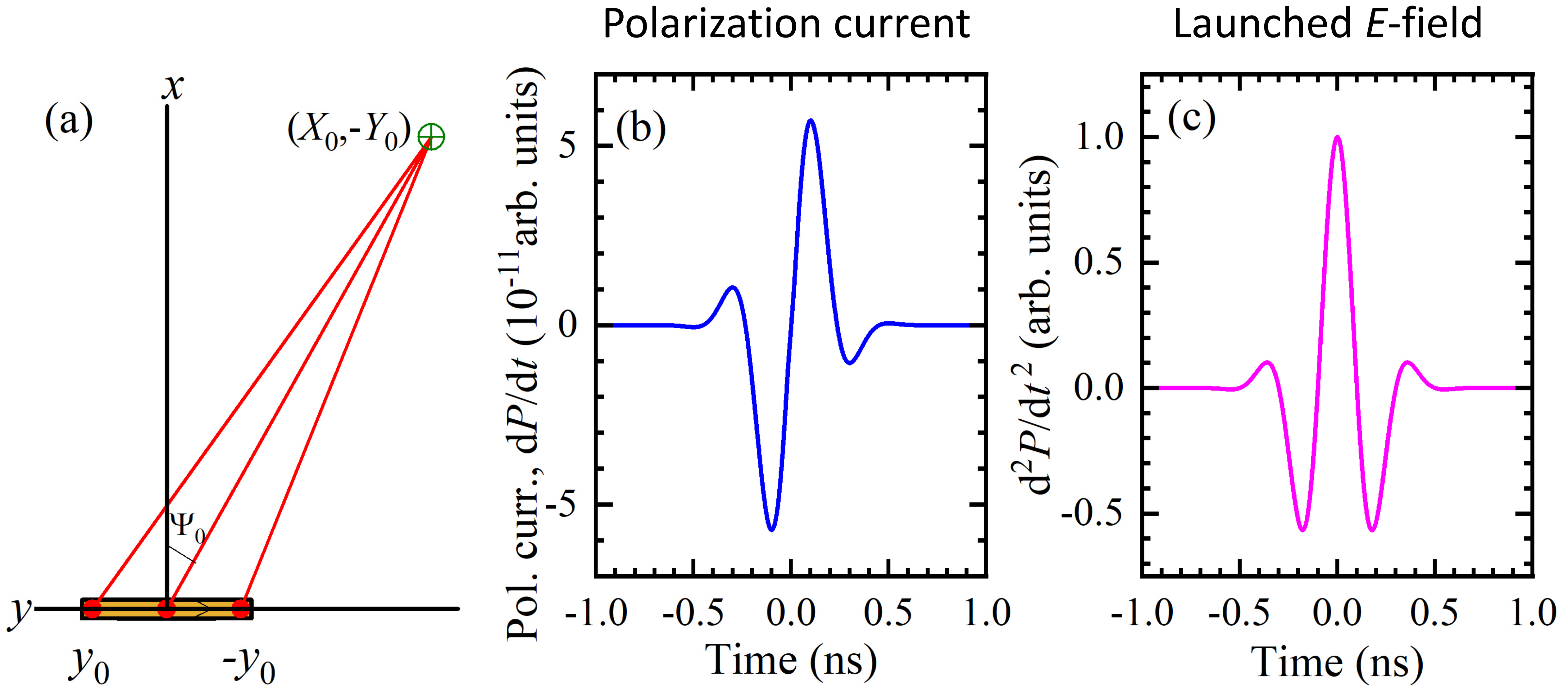
What's happening?

Concept: run the antenna so that a small blob of polarization current travels such that the component of its velocity towards a target ⊕ is always *c.*

The motion of the blob/source exactly compensates for the difference in path lengths between the emission and reception points *only in case* (a).

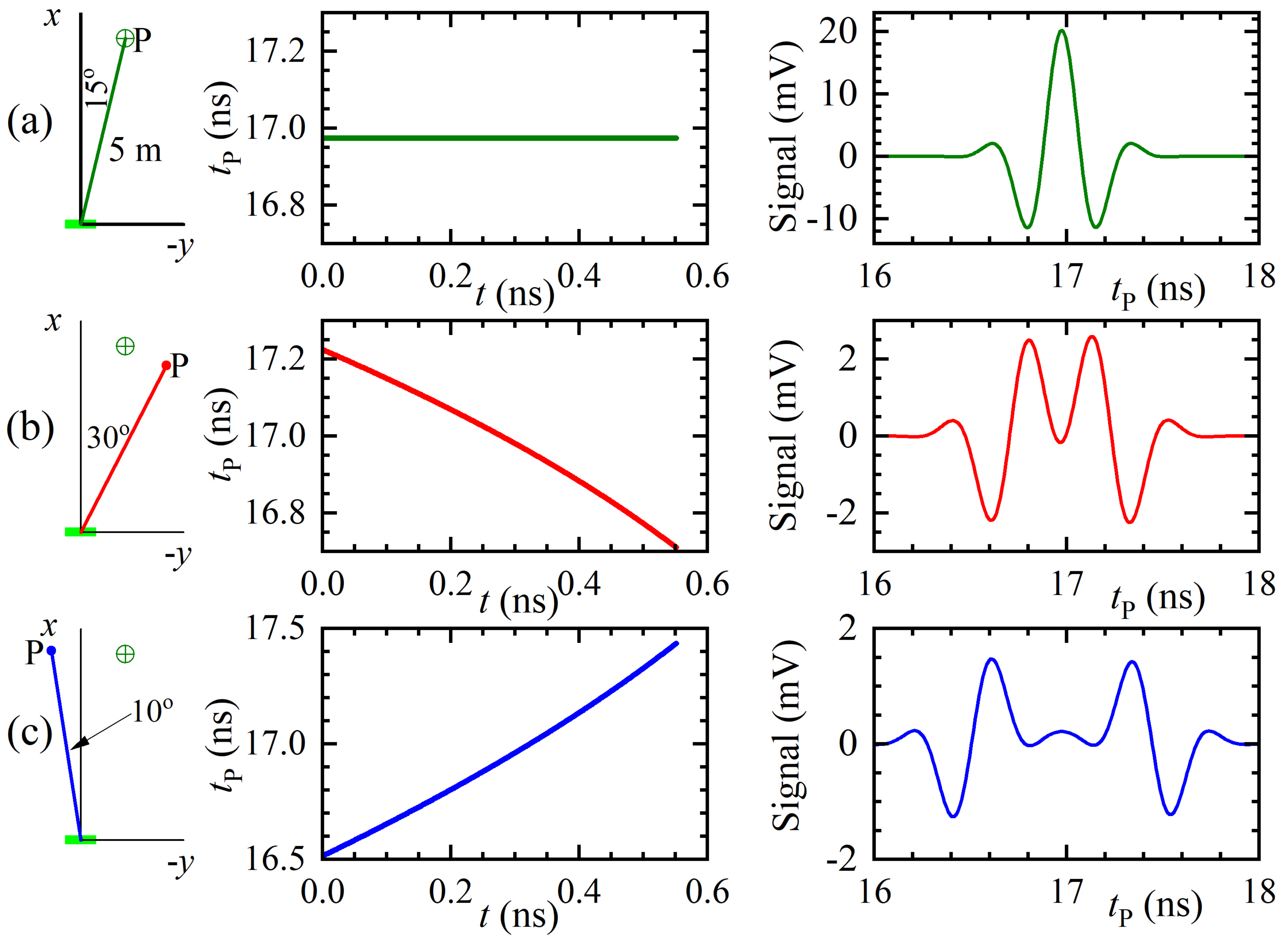


We now send a polarization current wavepacket along the antenna. Each point on the wave packet follows the same acceleration scheme as the blob discussed before.



Information focus:

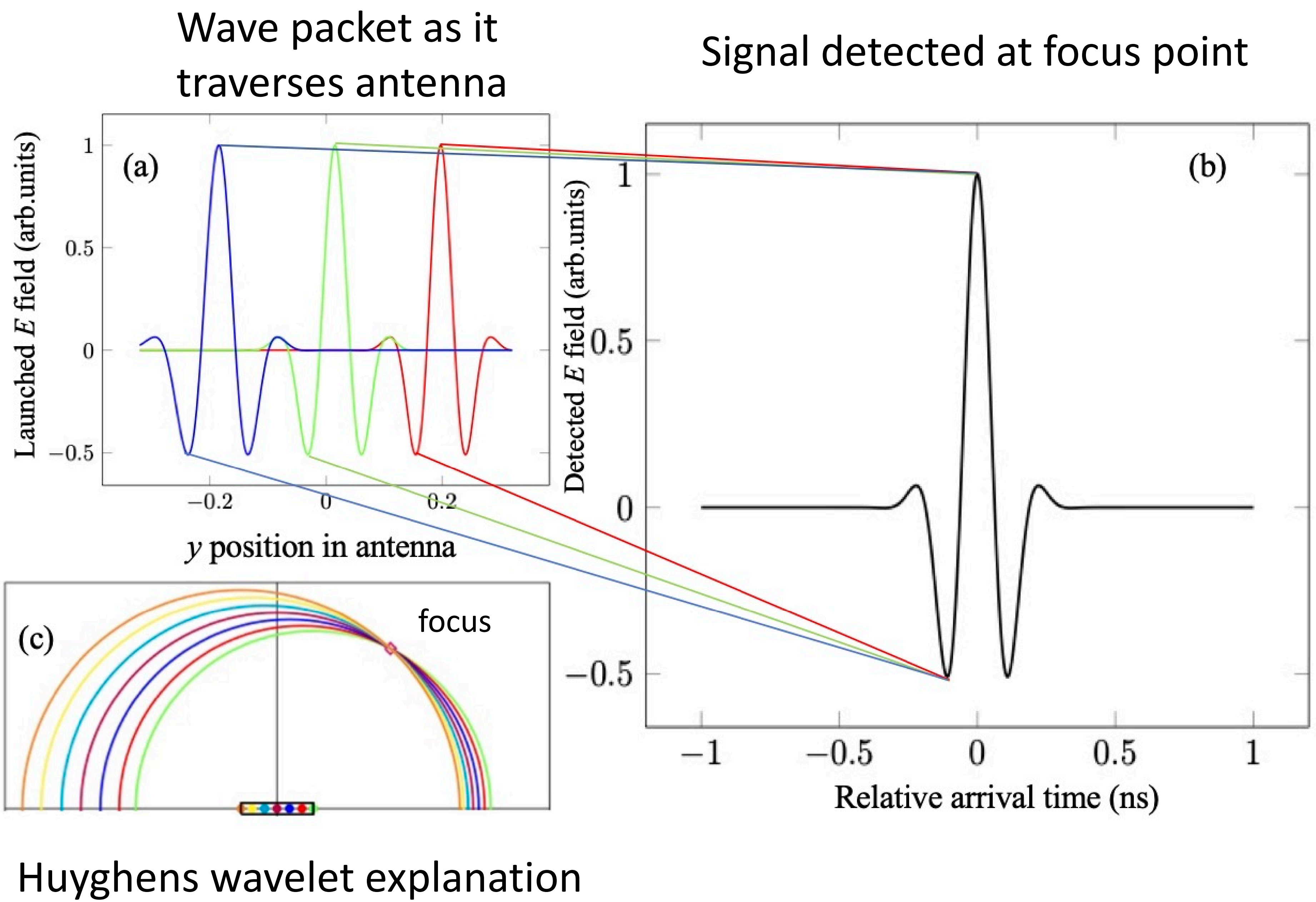
At the target angle and distance, detected signal reproduces the shape of the launched *E*-field exactly. Away from the target position, detected signal is much smaller and has altered frequency content and shape.

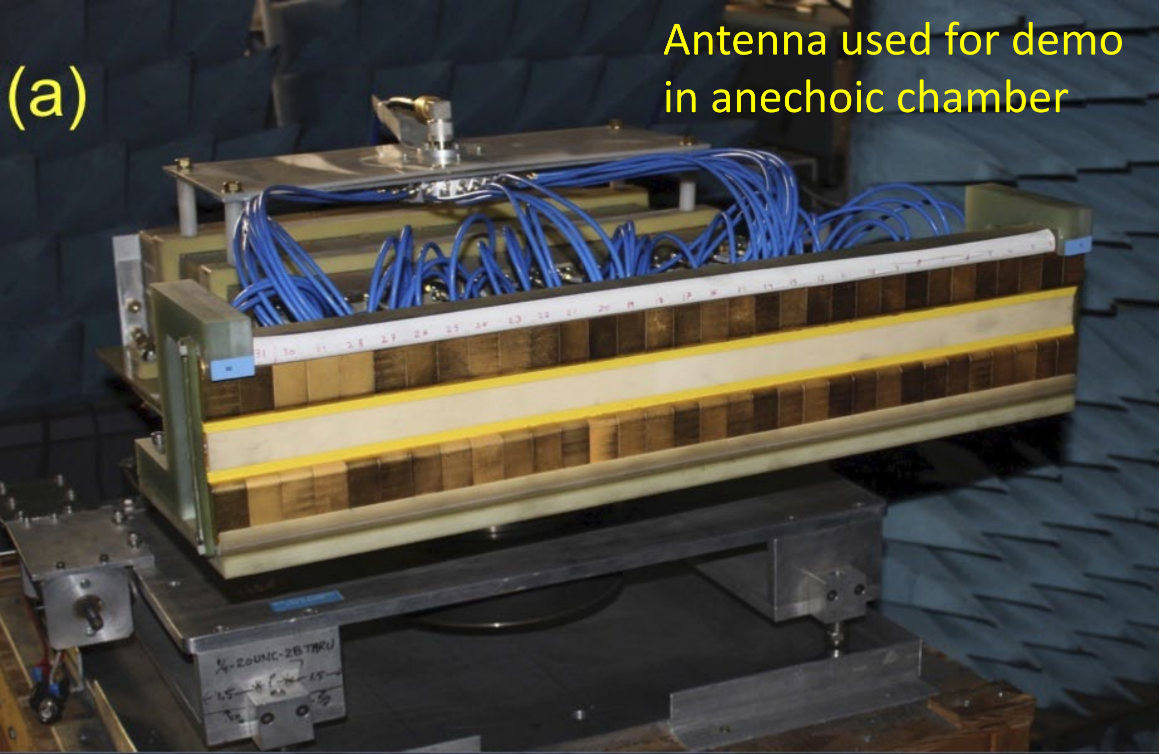


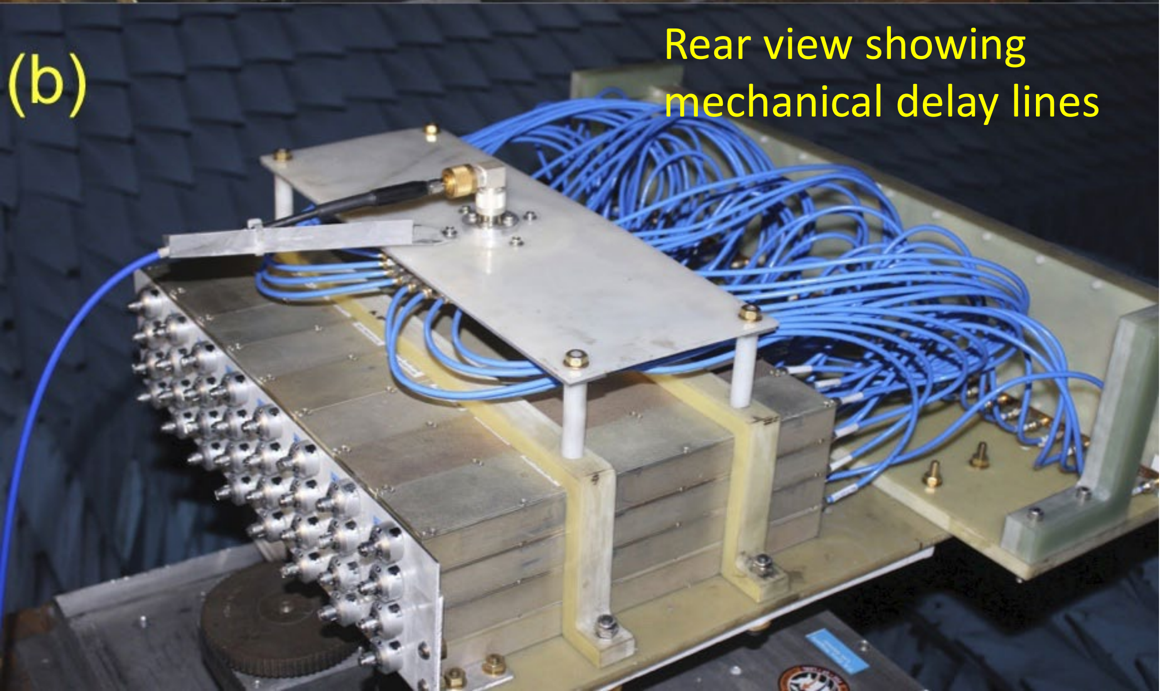
Explanation:

The acceleration scheme ensures that all emission from a particular point on the wavepacket as it traverses the antenna will arrive at the focus simultaneously.

Indeed, emission from any point on the wavepacket will behave similarly, the arrival time being the time at which that point entered the antenna at $y = y_0$ plus the time taken for light to travel from $(0,y_0)$ to the target.

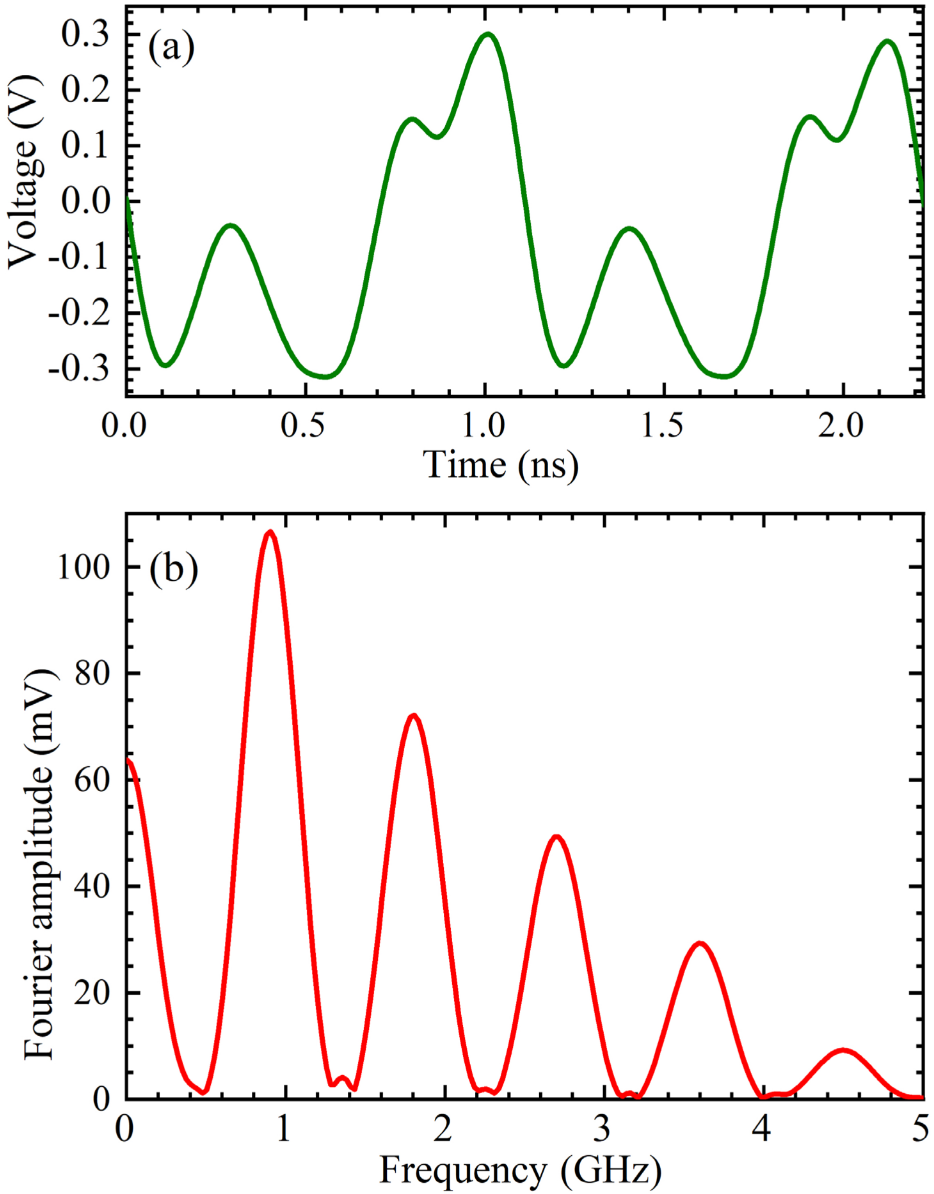


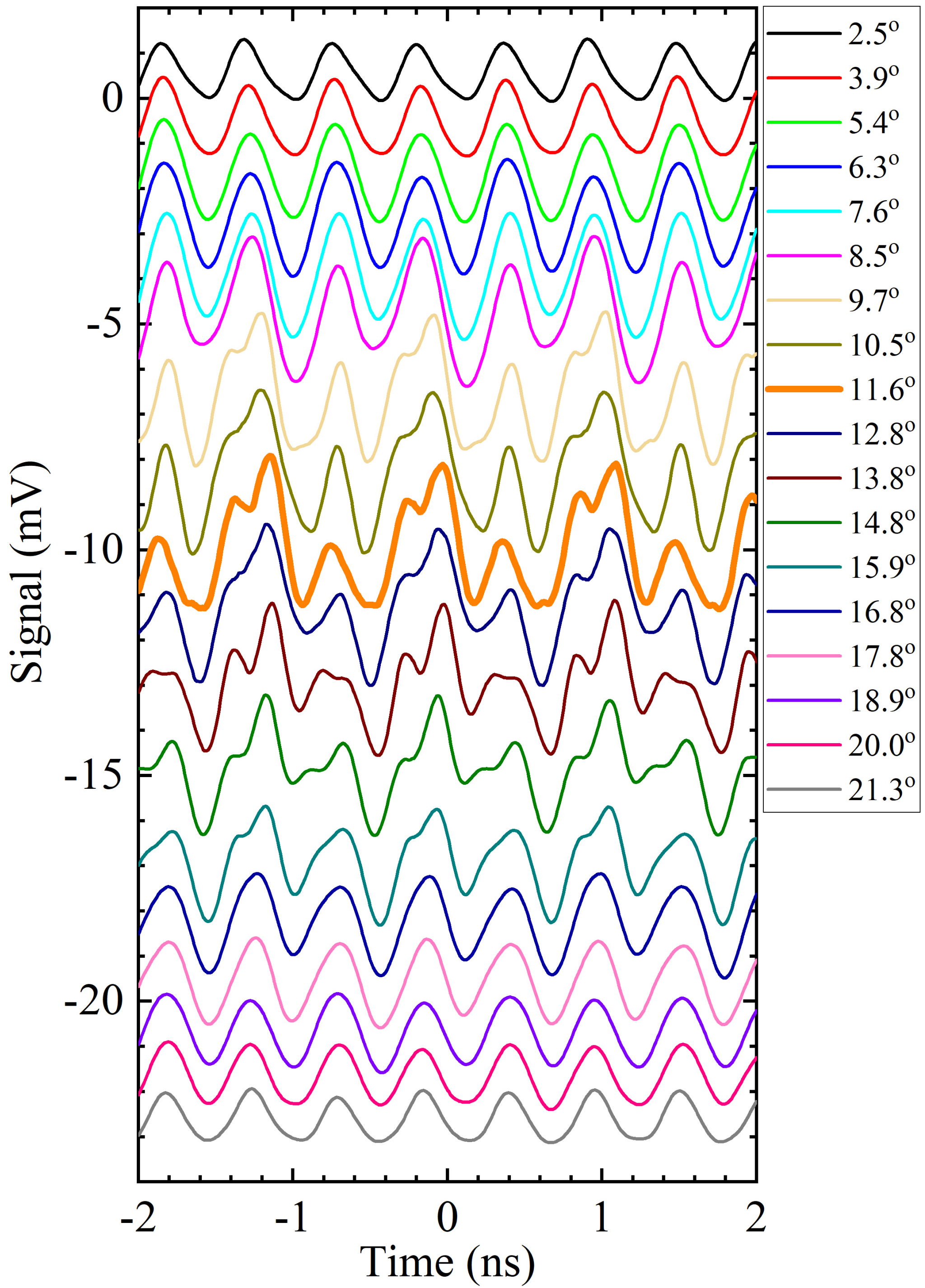




Right: broadcast *E*-field (a) and its Fourier transform (b). Note the simple form of the FT- a triangular envelope- makes the correct signal easy to find. Set acceleration for target coordinates: 3m @ 11.6° .

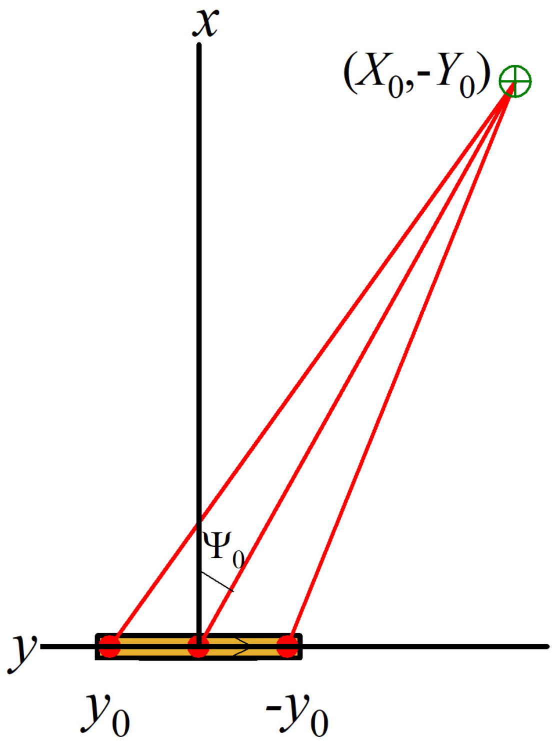
Experimental demo

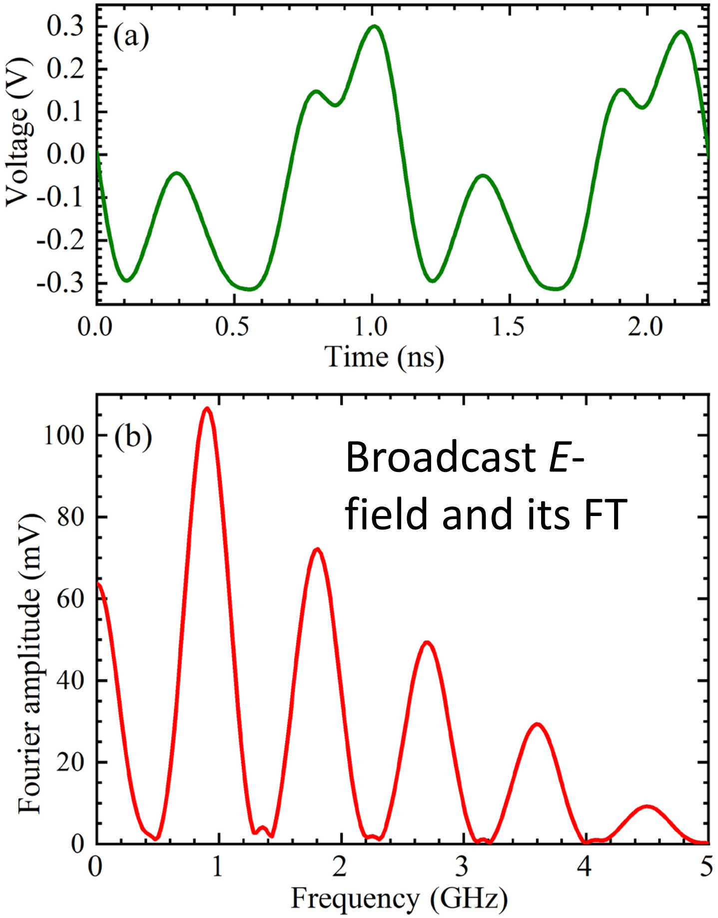




Place detector dipole at target distance of 3.0 m away from antenna and record detected *E*-field at several closely spaced angles.

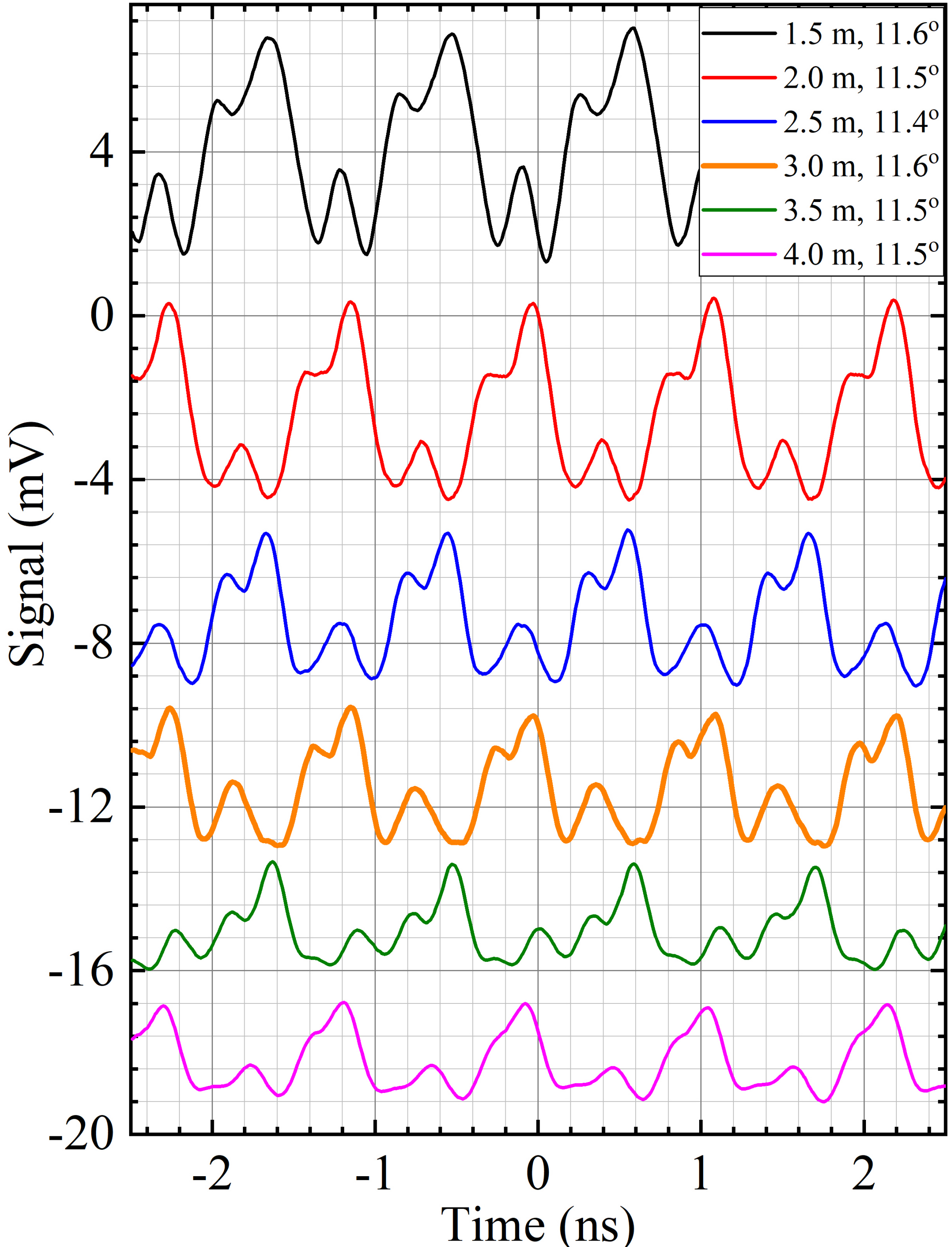
The shape of the broadcast *E*-field is only reproduced at the target angle of 11.6° (orange trace).

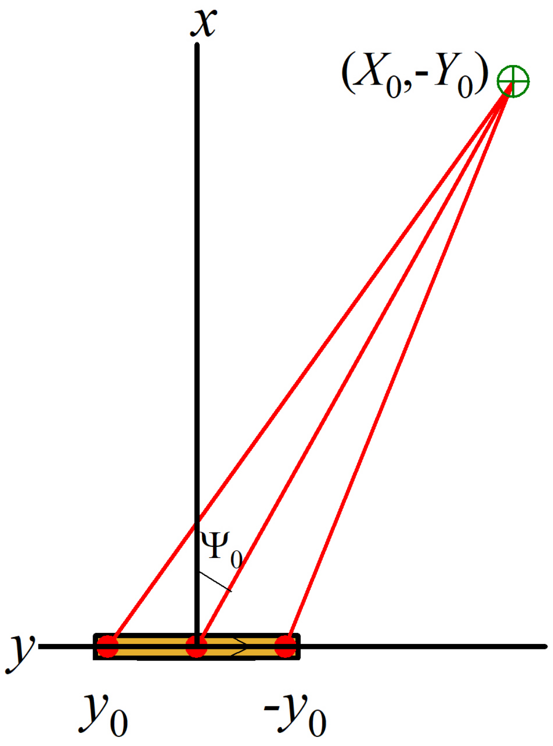


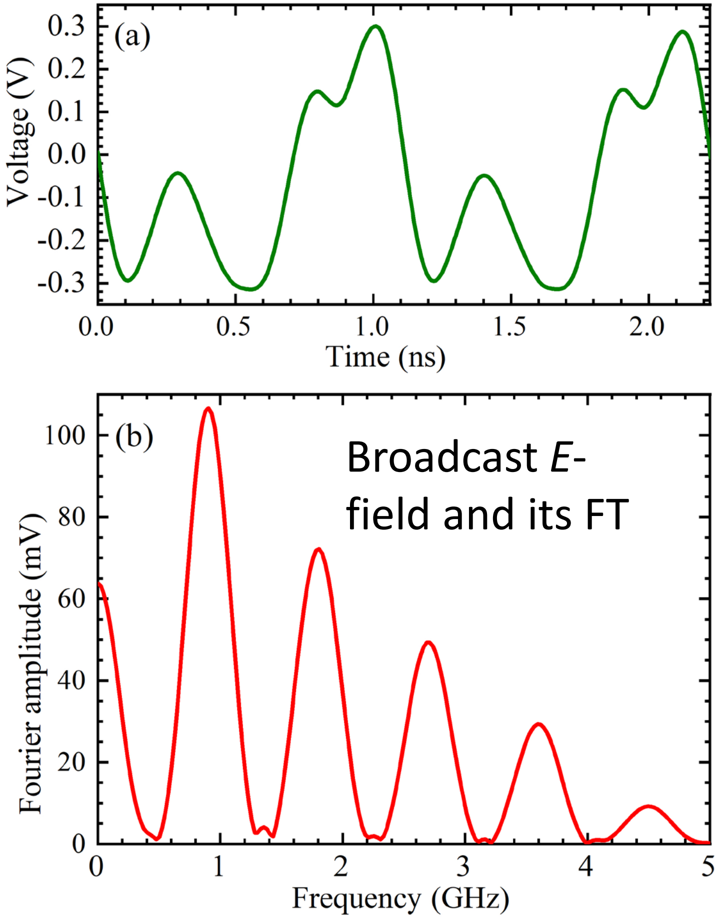


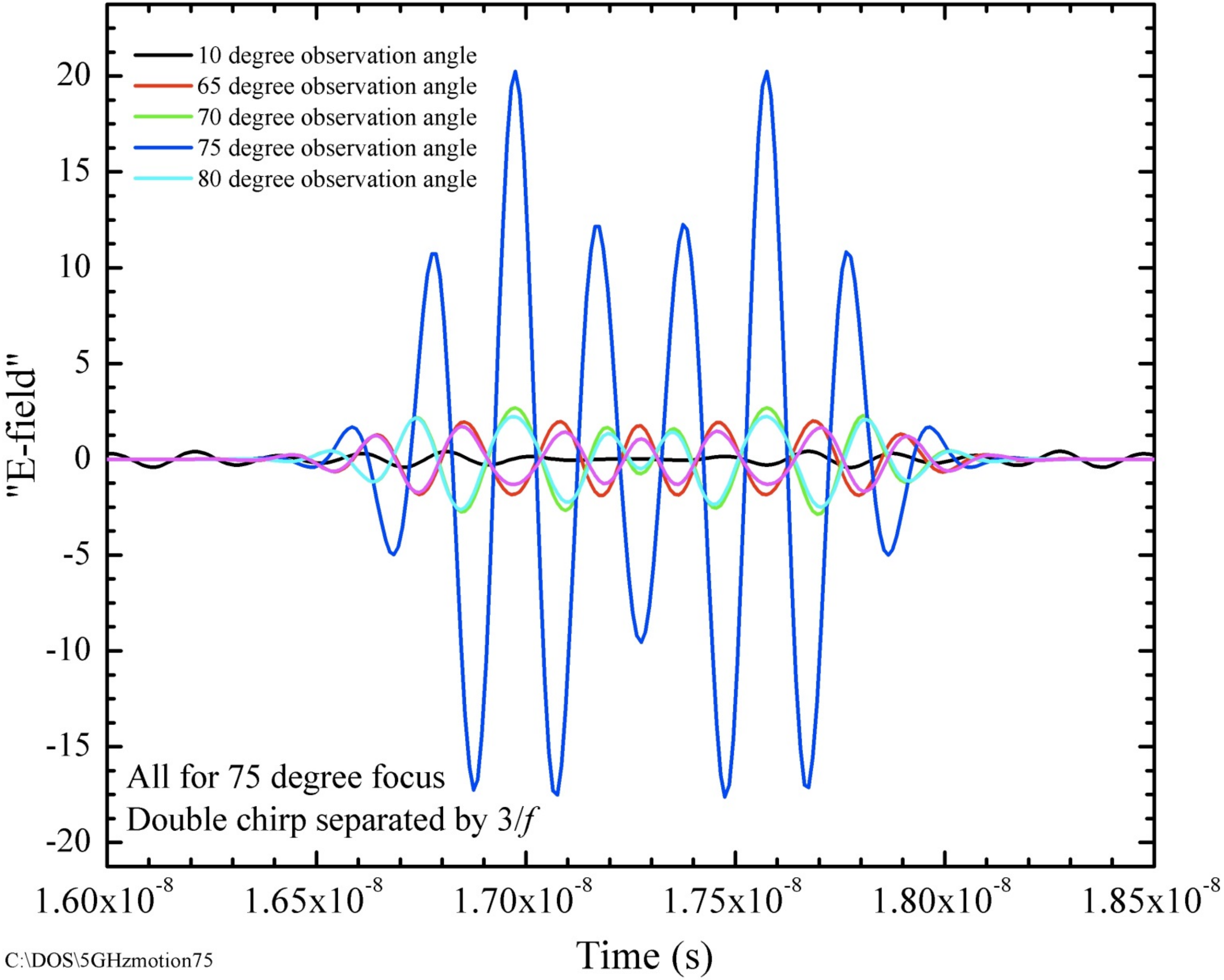
Place detector dipole close to target angle (11.6º) and record detected *E*-field at several distances.

The shape of the broadcast *E*-field is only reproduced at the target distance (3.0 m - orange trace).









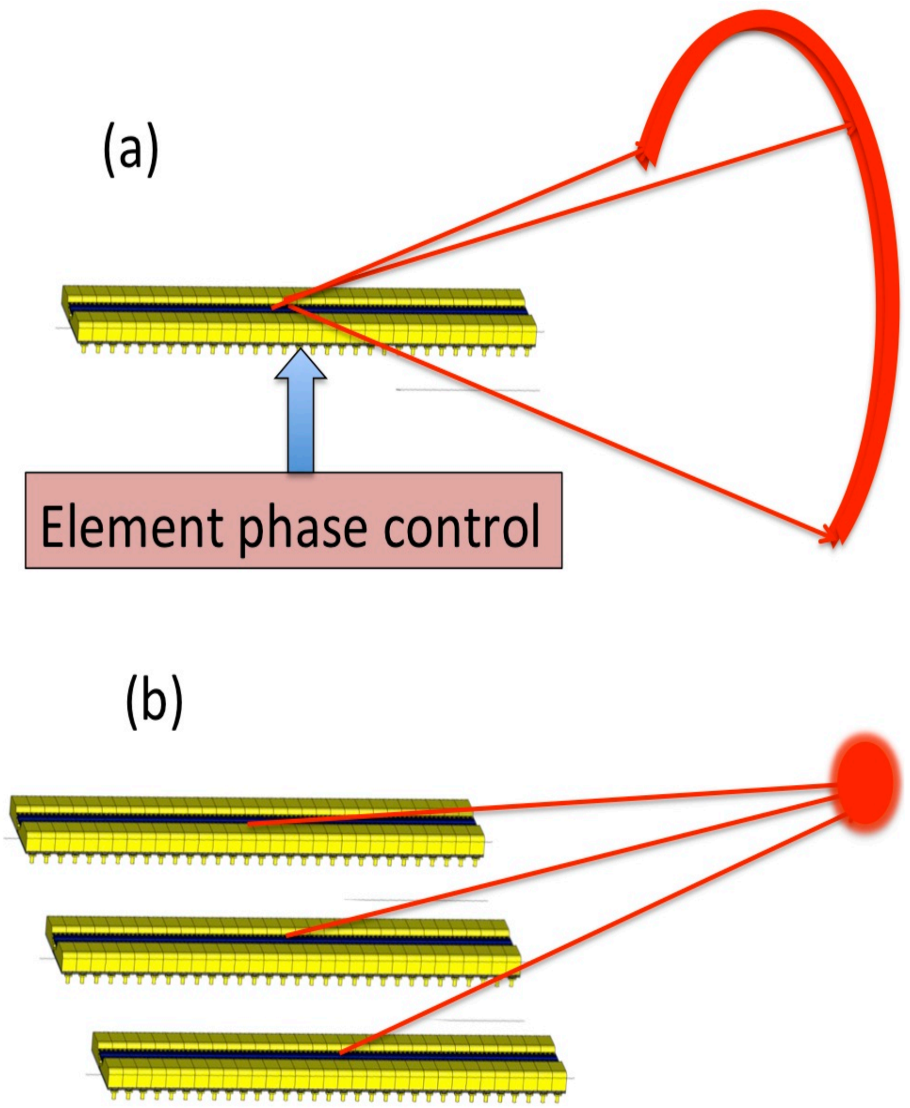
Modulated signal (double wavepacket)

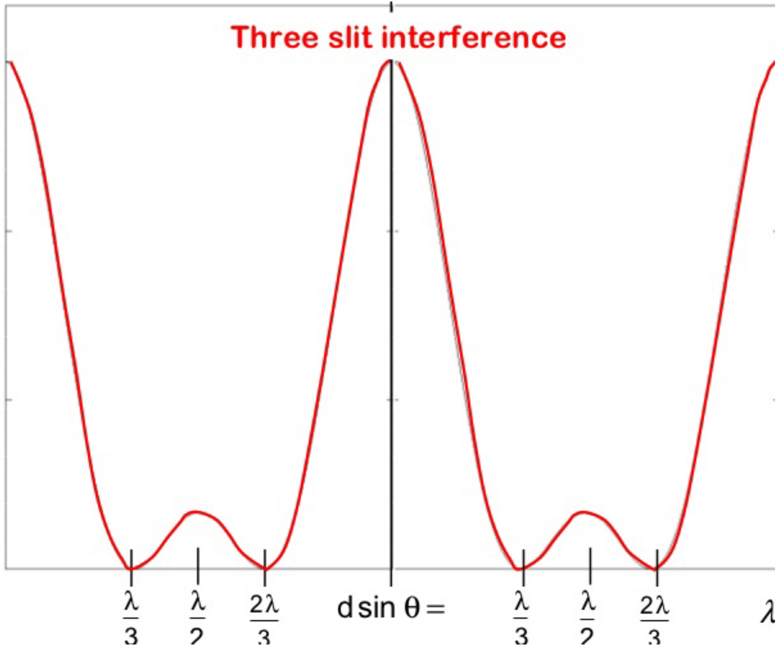
"Bits"- two wavepackets separated by the time equivalent of the "Rayleigh criterion".

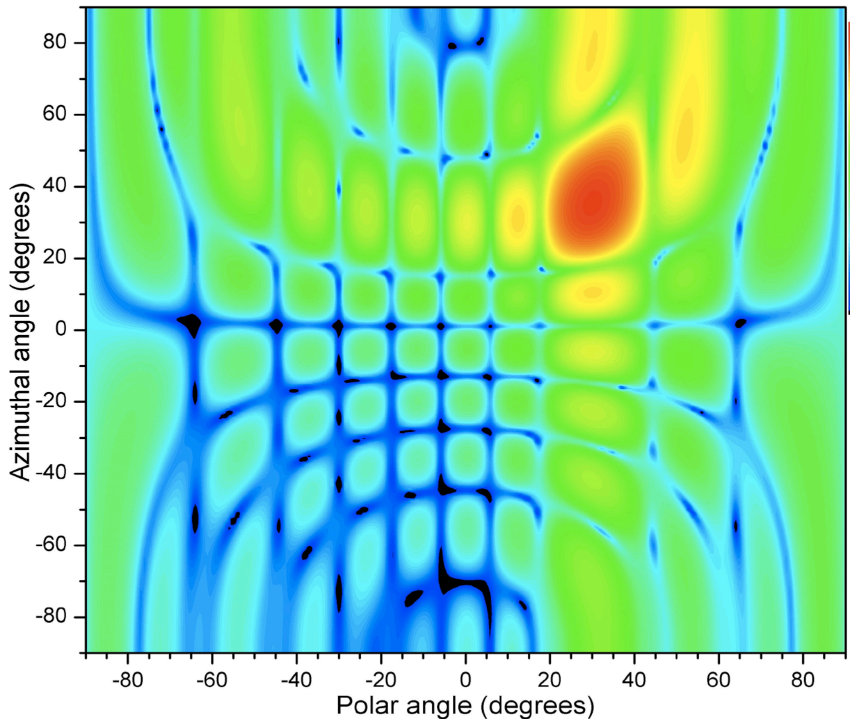
The proper shape of the double wavepacket signal is reproduced at the target angle, but nowhere else: information is only easily understood at desired location.

Three-dimensional information focus using array of three antennas:

- Convolute polar focus due to acceleration within each antenna with a three-slit diffraction pattern.
- Steer in azimuthal direction using a phase offset between each antenna in array.
- Single area of information focus (red) is possible.







Summary- a new way of communicating by wireless

- The experiments show that a continuous, linear, dielectric antenna in which a superluminal polarization-current distribution accelerates can transmit a broadband signal that is reproduced comprehensibly only at a chosen target.
- Requirement: each point in the polarization-current distribution approaches the observer/detector at the speed of light at all times during its transit along the antenna.

Conventional radio transmission methods: signals broadcast with little or no directivity; selectivity is from the use of one or more narrow frequency bands.

New technique: a spread of frequencies transmits information to a particular location; the signal is weaker and has a scrambled time dependence elsewhere. To receive, you have to be at the right place. Possible applications- 5G neighbourhood networks.

A completely new problem in mathematical physics requires an ab-initio mathematical treatment. This work was originally motivated by the fact that the radiation data collected from our practical machines did not match predictions made by others. It all begins with Maxwell's equations and ends with a fundamental causal solution that can be used to model the emission from polarization currents with regular domains of integration.

Maxwell's Equations

E, H = Electric and magnetic field intensity

D, B = Electric and magnetic flux density

ρ = Electric charge density

J = Current density of free charges

$$\nabla \cdot \mathbf{D} = \rho,$$
$$\nabla \cdot \mathbf{B} = 0,$$
$$\nabla \times \mathbf{E} = -\frac{\partial}{\partial t}\mathbf{B},$$
$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial}{\partial t}\mathbf{D},$$

Constituent Relations

μ = magnetic permeability

ε = electric permittivity

$$\mathbf{B} = \mu\mathbf{H},$$
$$\mathbf{D} = \varepsilon\mathbf{E}.$$

Inhomogeneous wave equations that govern the fields

$$\nabla^2\mathbf{E} - \varepsilon\mu\frac{\partial^2}{\partial t^2}\mathbf{E} = \frac{1}{\varepsilon}\nabla\rho + \mu\frac{\partial}{\partial t}\mathbf{J}$$

$$\nabla^2\mathbf{H} - \varepsilon\mu\frac{\partial^2}{\partial t^2}\mathbf{H} = -\nabla \times \mathbf{J}.$$

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In general form:

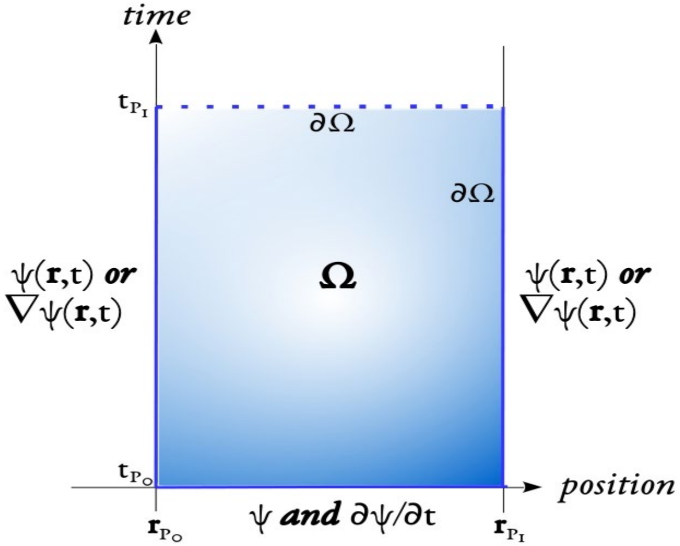
c = wave speed

r = a point (x,y,z) in a Cartesian coordinate system

q = source of electromagnetic radiation

$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right)\psi(\mathbf{r},t) = 4\pi q(\mathbf{r},t) \qquad \text{in } \mathbb{R}^3 \times (0,\infty)$$

By itself, this equation is meaningless as a problem of mathematical physics. To find physically relevant solutions we need to define the state of the system at some initial time t (initial conditions) and the conditions at the boundary of the problem domain (boundary conditions).



We choose Cauchy initial conditions (i.e., both, $\psi(r,t_0)$ and $\partial\psi(r,t_0)/\partial t$ and Dirichlet or Neumann boundary conditions (i.e., $\psi(r,t)$ or $\nabla\psi(r,t)$ but not both!) on an open surface. The problem domain is Ω with boundary $\partial\Omega$.

Many calculations later we arrive at the full Green's function solution with satisfaction of all initial and boundary conditions

$$\psi(\mathbf{r}_\mathrm{P}, t_\mathrm{P}) = u(\mathbf{r}_\mathrm{P}, t_\mathrm{P}) + v(\mathbf{r}_\mathrm{P}, t_\mathrm{P}) + w(\mathbf{r}_\mathrm{P}, t_\mathrm{P})$$

where

$$u(\mathbf{r}_\mathrm{P}, t_\mathrm{P}) = \int_{t_{P_0}}^{t_\mathrm{P}+} \mathrm{d}t \int_\Omega \mathrm{d}^3\mathbf{r}\; G(\mathbf{r}_\mathrm{P}, t_\mathrm{P}|\mathbf{r}, t) q(\mathbf{r}, t)\,,$$

Volume integral: source term

$$v(\mathbf{r}_\mathrm{P}, t_\mathrm{P}) = \frac{1}{4\pi} \int_{t_{P_0}}^{t_\mathrm{P}+} \mathrm{d}t \int_{\partial\Omega} \mathrm{d}^2\mathbf{r}\; \hat{n} \cdot \Big[G(\mathbf{r}_\mathrm{P}, t_\mathrm{P}|\mathbf{r}_{\partial\Omega}, t) \boldsymbol{\nabla} \psi(\mathbf{r}_{\partial\Omega}, t) - \left[\boldsymbol{\nabla} G(\mathbf{r}_\mathrm{P}, t_\mathrm{P}|\mathbf{r}_{\partial\Omega}, t)\right] \psi(\mathbf{r}_{\partial\Omega}, t) \Big]\,,$$

Surface integral: boundary term → disappears in free space

and

$$w(\mathbf{r}_\mathrm{P}, t_\mathrm{P}) = -\frac{1}{4\pi c^2} \int_\Omega \mathrm{d}^3\mathbf{r} \left[\frac{\partial G(\mathbf{r}_\mathrm{P}, t_\mathrm{P}|\mathbf{r}, t_{\mathrm{P}_0})}{\partial t} \psi(\mathbf{r}, t_{\mathrm{P}_0}) - \frac{\partial \psi(\mathbf{r}, t_{\mathrm{P}_0})}{\partial t} G(\mathbf{r}_\mathrm{P}, t_\mathrm{P}|\mathbf{r}, t_{\mathrm{P}_0}) \right].$$

Initial state of the system → can always be set equal to 0 for "null initial conditions"

Green's functions in action: Comparison of the model to experimental data:

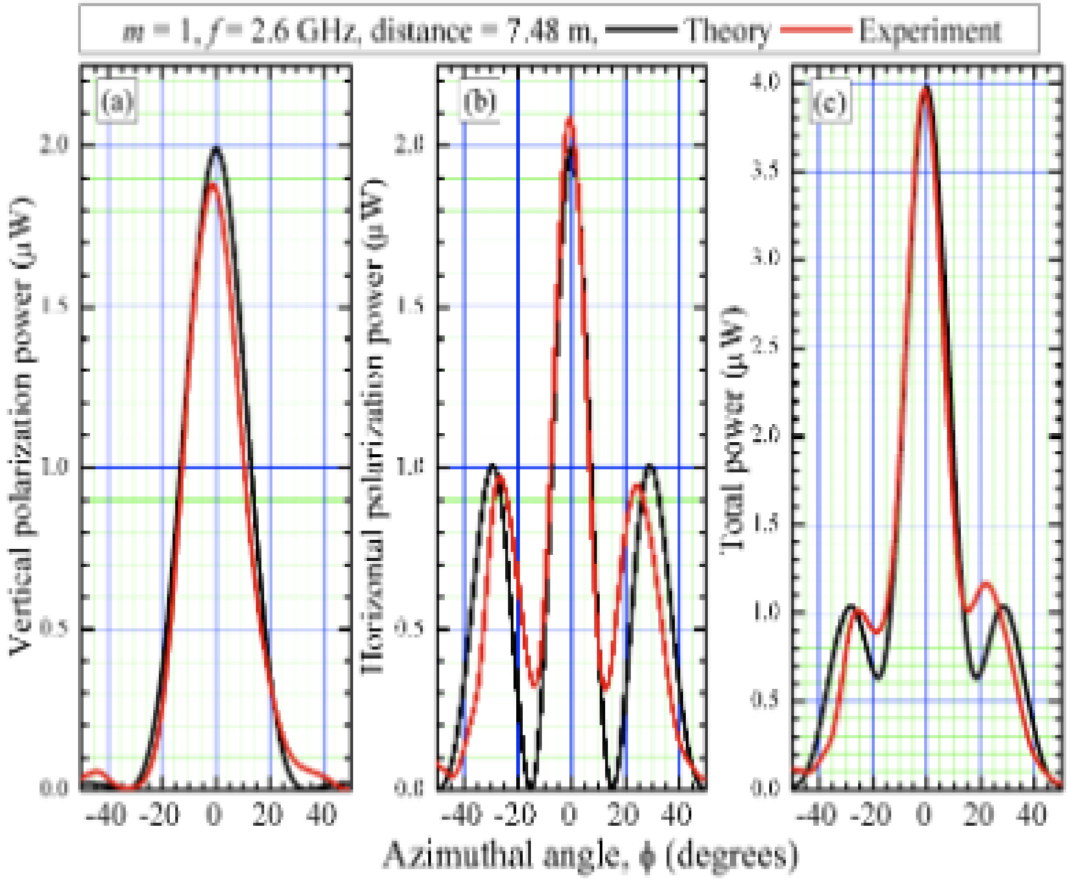


Figure 7.7: Model (black) of circular antenna TD 1 ($m = 1$, $f = 2.6$ GHz) compared with experimental data (red) measured in the FARM Anechoic Chamber: (a) vertical polarization power; (b) horizontal polarization power; (c) total power. Powers are in μW and other parameters are in the key.

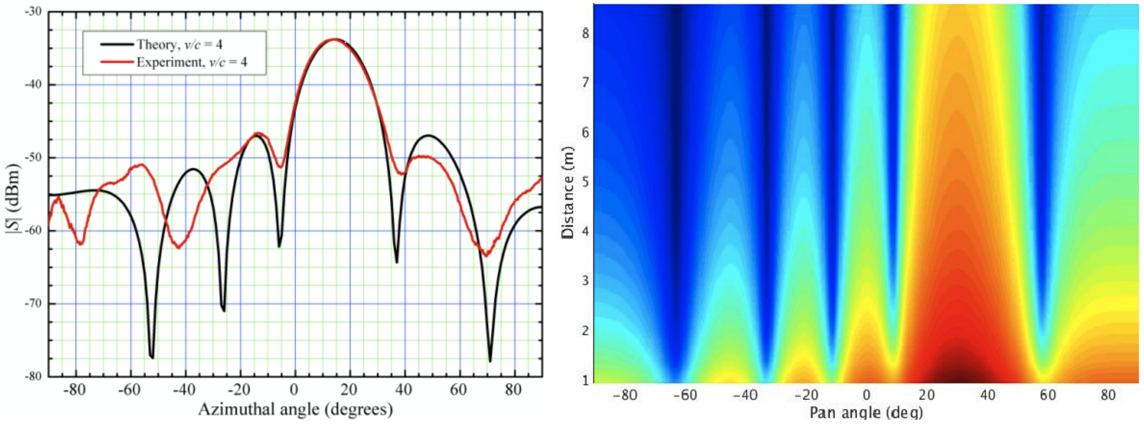


Figure 7.3: Left: modulus of Poynting vector $|S|$ versus azimuthal (pan) angle φ (black) predicted by the model of TD 2 (Fig. 3.1, center panel). The frequency is 2.4 GHz, $v/c = 4$ and the antenna to detector distance is 5 m. Experimental data for the same antenna, measured at the same distance (5 m) in the Sandia FARM anechoic chamber are shown in red. After correction for the gain of the detector antenna, there is a very good quantitative match between experiment and theory. Right: modulus of Poynting vector $|S|$ (colour contours) versus azimuthal (pan) angle φ and distance predicted by the model of the linear superluminal antenna. The frequency used was 2.5 GHz and the source speed was $v/c = 2$. The simulation is in good agreement with experimental data measured in the FARM and TA-35 anechoic chambers.